# Carbon pricing in the aviation sector: A sector-specific approach to CO2 abatement potential and cost

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# Carbon pricing in the aviation sector

## A sector-specific approach to $CO_2$ abatement potential and cost

**Master EDDEE**
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# INTRODUCTION

The aviation sector is a key target of international climate negotiations. Indeed, its greenhouse gas emissions have recorded tremendous growth trends over the past twenty years and still show strong momentum. In this context, several questions emerge as to how much emission reduction can be achieved in this oil-dependent sector, at what cost to the industry and to the global economy, and based on which policy levies. This introduction aims at clarifying the stakes of greenhouse gas emission reduction in the aviation sector with regards to environmental protection, economic balance and public policy design.

***Aviation's role in world economy***

With a record 2.28 billion passengers in 2009 and 24,000 aircraft in commercial service (ICAO, 2009), air transport contributes significantly to the global economy. In the European Union alone, it accounted for about 220€ billion of added value and 4.5 million jobs in 2004, taking direct, indirect and induced effects into account (ATAG, 2008; AEA, 2010). Furthermore, aviation has a strong catalytic effect on other sectors of the economy, as it enables other industries to operate and perform more efficiently and is facilitator to world trade. Thus, worldwide, the economic impact of aviation is estimated to be around 32 million jobs and $3.560 billion added value (direct, indirect, induced and catalytic), which is equivalent to 7.5% of world GDP (ATAG, 2010).

However, aviation is faced with important challenges when it comes to securing the conditions for its sustainable development.

***Three main challenges to aviation's sustainable development***

Based on the definition suggested by Sgouridis (see Sgouridis *et al.*, 2010), a sustainable air transport system would have a negligible environmental footprint (environmental sustainability) while satisfying the transportation needs of a globally connected society (social sustainability) and providing adequate returns on investment to attract and retain investors, employees, and the supporting value chain (economic sustainability).

First, it is faced with an energy challenge due to its dependence on crude oil. Indeed, both the continued physical availability and the economic affordability of fossil fuels are high stakes for the transport sector as a whole and for aviation in particular (see Table 0-1). This calls for a coherent research strategy on alternative jet fuels, regulatory enablers and streamlined certification and approval processes, as well as the establishment of sustainable supply chains (EC, 2011).

**Table 0-1 – Growth rates of transport energy use, 1990-2006**

| | OECD | | | | Non-OECD | | | |
|---|---|---|---|---|---|---|---|---|
| Year Period | 90-95 | 95-00 | 00-06 | 90-06 | 90-95 | 95-00 | 00-06 | 90-06 |
| International aviation | 4.4% | 5.0% | 1.2% | **3.4%** | -0.6% | 1.7% | 4.7% | **2.1%** |
| Domestic aviation | -0.2% | 2.5% | -0.3% | **0.6%** | -0.5% | 4.9% | 3.0% | **2.5%** |
| Road | 2.3% | 2.1% | 1.4% | **1.9%** | 2.5% | 2.9% | 4.2% | **3.3%** |
| Rail | -0.1% | -0.3% | 2.3% | **0.7%** | -4.4% | 2.9% | 2.3% | **0.3%** |
| International marine bunkers | 1.1% | 2.3% | 2.5% | **2.0%** | 4.6% | 3.9% | 5.4% | **4.7%** |
| Domestic navigation | 0.8% | 0.5% | -1.0% | **0.0%** | -2.6% | 6.5% | 4.0% | **2.6%** |
| **Transport sector** | 2.1% | 2.1% | 1.2% | **1.8%** | 1.1% | 2.6% | 4.3% | **2.8%** |

*Source:* IEA, *Transport, Energy and $CO_2$ Emissions* (2009)

Second, the aviation industry is exposed to high financial and economic challenges because of airlines' historically weak financial balance sheet and to an ever fiercer competition. Airlines' economic viability and solvency are key conditions for higher investment in technology that is needed to adapt to an increasingly complex aviation system (EC, 2011). Finally, aviation is faced with increasing environmental challenges. While it has historically confronted its impacts in terms of noise pollution and local air pollution in airports' surroundings, aviation has stayed on the sidelines of multilaterally-coordinated action on climate change for its international activity – for the record, only domestic aviation is *de facto* accounted for in the Kyoto Protocol's national commitments. Being increasingly targeted for its impact in terms of greenhouse gas emissions, aviation has engaged in a more comprehensive internalizing of its environmental externalities.

***A focus on aviation's impact on environment***

As already stated, aviation's impact on environment is mainly threefold. Historically, noise pollution has been the first of aviation's environmental impact to become a public issue in the 1960s. The ICAO established noise standards for the reduction of noise at source (from the engine's blower, combustion chamber, turbine and exhaust pipe). Other measures for aircraft noise mitigation have included improved land use planning and control around airports (based on noise zoning instruments and noise insulation programmes), wider use of noise abatement operational procedures for take-off and landing, operating restrictions for the noisier aircraft types (based on noise standards), night flying restrictions for specific airports, as well as noise-related airport charges for incentivizing the use of quieter aircraft and off-peak operations. This portfolio of measures has allowed for noise abatement of around 20 dB as compared to first jets (ICAO).

Besides, local air quality around airports also soon emerged as a priority public concern. Nitrous oxides (NOx) emissions on the ground and up to 3000m altitude are ozone precursors on the one hand, and on the other hand they are acknowledged to have a direct impact on human health in the airport surroundings. The ICAO has implemented the first regulatory norms for gaseous pollutants for newly produced large jet engines in the late 1960s. Those standards have been revised every 8 years approximately, reflecting a progressive stringency about this local pollution from aviation.

Finally, aviation is under ever sharper scrutiny for its greenhouse gas emissions for it is a fast-growing sector, with no available alternative to fossil energy fuelled jet engines in the very short term, and currently no obligation under international law to mitigate its emissions. However, specialised literature often underlines the existence of trade-offs between different types of emissions from aviation. Indeed, it appears nowadays aircraft jet engines have reached such a degree of optimisation according to specific parameters (e.g noise or nitrous oxides emissions) that the design of new engines in a $CO_2$-optimisation perspective might occur at the expense of increasing their nitrous oxides emissions (ITF, 2008). Another often-mentioned trade-off is that of turbopropellers which allow for reduced $CO_2$ emissions while increasing noise emissions with current technologies.

***Aviation's share in global GHG emissions***

As stated by all scientific literature on the topic, estimating the impact of aviation's GHG emissions is complicated by a number of uncertainties. Aviation emitted about 750 million tonnes of $CO_2$ from fuel combustion in 2008, about 11.4% of all transport $CO_2$ emissions and 2.6% of total $CO_2$ emissions from fuel combustion (see Table 0-2). Though representing a small proportion of world emissions, international aviation $CO_2$ emissions are growing at a tremendous pace, almost twice as fast actually as world total $CO_2$ emissions over the period 1990-2008.

**Table 0-2 – Share of aviation in world $CO_2$ emissions from fuel combustion, 1990-2008**

| | World $CO_2$ emissions from fuel combustion (Mtonnes) | | | | Increase | Emissions per capita (tonnes) |
|---|---|---|---|---|---|---|
| Year Period | 1990 | 2000 | 2005 | 2008 | 1990-2008 | 2008 |
| Total | 20,964.85 | 23,496.55 | 27,129.14 | 29,381.43 | 40% | 4.39 |
| **Transport** | **4,583.67** | **5,659.04** | **6,285.03** | **6,604.66** | **44%** | **0.99** |
| *Transport share of total* | *21.9%* | *24.1%* | *23.2%* | *22.5%* | | |
| **Aviation** | **539.03** | **674.69** | **732.52** | **752.19** | **40%** | **0.11** |
| Domestic | 280.81 | 320.27 | 310.95 | 297.34 | 6% | |
| International | 258.22 | 354.42 | 421.57 | 454.85 | 76% | |
| *Aviation share of transport* | ***11.8%*** | ***11.9%*** | ***11.7%*** | ***11.4%*** | - | |
| *Aviation share of total* | ***2.6%*** | ***2.9%*** | ***2.7%*** | ***2.6%*** | - | |

*Source:* ITF, *Reducing Transport Greenhouse Gas Emissions* (2010), from IEA *Data and Statistics*

Besides, some studies suggest that aviation's overall warming impact is much higher than primarily assessed from $CO_2$ emissions given its emissions of other GHGs, such as nitrous oxides (NOx), methane ($CH_4$) and water vapour ($H_2O$), as well as differentiated effects of emissions at different altitudes such as formation of cirrus clouds and contrails (IPCC, 1999). However, as there is high uncertainty about the net effects of all GHG emissions from aviation in terms of radiative forcing and global warming power (see Appendix 1 for further detail on the overall assessment of GHG emissions from aviation), this paper will focus on $CO_2$ emissions from aviation's fuel combustion.

In IPCC's reference scenario for aviation emissions (IPCC, 1999), $CO_2$ emissions from aviation are assumed to increase threefold by 2050 as compared to 1990 levels, thus representing 3% of the projected total anthropogenic $CO_2$ emissions relative to the mid-range IPCC emission scenario. The ICAO has drafted similar forecast for aviation emissions growth, with a fourfold increase in aviation fuel burn by 2050 under the assumption of a 1% yearly improvement in fuel use efficiency (as opposed to previous 2% average in the past).

***The industry's commitment to reduce GHG emissions***

Confronted with ever growing pressure to take action on its climate impact, the industry has recently voiced its commitment to reduce its GHG emissions.

The IATA's Carbon Neutral Initiative, published in June 2009, advocates a four-pillar voluntary strategy to address the carbon footprint of aviation, based on *i)* improving technology, *ii)* improving operations, *iii)* improving infrastructure, and *iv)* implementing economic measures. This strategy aims at three sequential goals of improving fuel efficiency by an annual average of 1.5% by 2020 (per seat- or tonne-kilometre performed), then capping net carbon emissions from 2020 onwards (through carbon neutral growth), and eventually halving $CO_2$ emissions per seat- or tonne-kilometre performed by 2050 as compared to 2005 levels. This airlines-driven initiative postulates that 2050 targets should be mainly achieved through aircraft technology improvements for new aircraft and to a lesser extent by aircraft operation improvements and the blending of biofuels (IATA, 2009c). This initiative has received support from ATAG, an association that includes all kinds of companies and organisations in the aviation sector, including aircraft and parts manufacturers, airports and air navigation services providers.

Following much talks at the international level and pressure from the UN-led climate change multilateral institutions, the ICAO has endorsed the industry's goals as regards $CO_2$ emissions. They indeed made official in 2010 a 2% global annual fuel efficiency improvement target over both medium (2020) and long (2050) terms, calculated on the basis of volume of fuel used per tonne-kilometre performed.

In the absence of legally-binding targets or ICAO-harmonised path for the mitigation of aviation's impact on climate at the present, it is worth noticing that there are significant differences between the US and the EU approaches to reducing aviation's environmental impact, underlining the variety of options towards the same goal. From a policy perspective, the US tend to place technology at the heart of aviation's environmental strategy, as illustrated by the scope and structure of the NextGen Programme for air traffic management modernisation (see Parts 1 and 2 for further detail), while the EU has so far focused on standards to drive technological improvements. After publishing a quite ambitious 2020 vision in 2001 based on the ACARE programme (targets of 50% reduction in fuel burn in 2020 as compared to 2000, 80% reduction in NOx emissions, and halved perceived noise, supported by research programmes such as SESAR ATM and CleanSky under ERFP), the European Commission published in 2011 a document, 'Flightpath 2050: Europe's Vision for Aviation', aiming at extending ACARE's achievements with an equally ambitious programme towards 2050, namely: a 75% reduction in $CO_2$ emissions per passenger-kilometre performed in 2050 as compared to 2000 levels, a 90% reduction in NOx emissions, and a 65% reduction in perceived noise emissions. The EU has however been quite innovative in promoting the use of emissions trading for the mitigation of aviation emissions. While the ICAO Assembly resolutions allowed for such measures to be implemented on a voluntary basis, the decision of the EU to include $CO_2$ emissions from all its inbound and outbound flights in the existing emissions trading scheme from 2012 on, has met strong opposition from the international community as coming close to being a unilateral action in "violation of international law" (US Air Transport Association).

***A summary of policy options to encourage GHG emissions reduction in aviation***

Faced with the complex task of fostering GHG emissions reduction in the aviation sector, public authorities can consider a wide portfolio of policy instruments. Table 0-3 lists a selection of emission reduction policy tools applicable to aviation from various sources. The criteria used for the evaluation of those instruments resort to both their environmental efficiency and their economic efficiency. Particular points of vigilance with regards to the design of GHG emissions-oriented policy instruments are, among others, the explicit link to emissions (for both an enhanced acceptability in the short-term and the emergence of a strong price signal for carbon emissions in the long-term), the risk of "carbon leakage" (from one actor to another, or from aviation to another transport mode), as well as the flexibility (in time and in space, in order to reduce emissions where and when it is most cost-efficient).

Based on a primary *a priori* assessment of policy instruments, the introduction of a carbon price in the aviation sector might act as an enabler of change towards a more efficient aviation system. Should it take the form of a tax or a market mechanism, pricing carbon in the aviation sector would constitute an explicit incentive for emissions abatement, with good cost efficiency.

**Table 0-3 – Summary of potential GHG emissions reduction policy tools**

| Policy tool | Environmental efficiency | Economic efficiency | Limits |
|---|---|---|---|
| **Mandatory emissions standards for aircraft** | Implementation at airport level (similar to airport noise standards): risk of carbon leakage to low-standard airports | Implementation at international level: potentially high cost of fleet renewal for airlines depending on standard level and progressiveness | Possible trade-offs with international noise and local air pollution standards |
| **Mandatory incorporation** | Highly dependent on | Sensitivity to feedstock | Availability of feedstock |

| | | | |
|---|---|---|---|
| **of biofuels** | sustainability criteria for biofuels' patterns | supply and processing costs | and readiness of processes<br>Risk of technological lock-in |
| **Restrictions on airport development** | Risk of substantial carbon leakage (to non-restricted airports, with potential additional emissions from car transport) | Potentially high cost to society | Poor acceptability |
| **ATC reforms** | Potential for high abatement | Potentially high modernisation costs for ATC suppliers<br>Potentially high, short term return for airlines | Limited bargaining power of airlines<br>Limited momentum of international ATC coordination |
| **Airport reforms** | Potential for high abatement | Potentially high, short term return for airlines | Limited bargaining power of airlines<br>Poor incentives for modernisation |
| **Taxes on air ticket** | Limited emissions reduction, achieved only through a decrease in air travel demand<br>Risk of carbon leakage to untaxed countries or exempted modes | Potentially high costs for airlines in case of partial cost pass-through to passengers<br>No guarantee that abatement occurs where it is most cost efficient | Poor acceptability in case use of revenue is disconnected from the sector |
| **Airport emissions-related charges** (similar to noise-related airport charges) | Risk of carbon leakage to low-charging airports<br>No link to effective GHG emissions for the whole flight | No guarantee that abatement occurs where it is most cost efficient | Poor acceptability |
| **Fiscal incentives on fleet renewal** (e.g. through adjusted accounting treatment of depreciation) | Emissions reduction achieved through fleet renewal in countries with favourable taxation<br>Risk of carbon leakage to countries with no favourable fiscal scheme | Potential windfall profits for airlines under the scheme<br>No guarantee that abatement occurs where it is most cost efficient | States' unwillingness to give up fiscal revenue |
| **Fuel/carbon taxes** | Risk of carbon leakage to untaxed countries or exempted modes<br>No guarantee of effective abatement | Cost effective since closely related to emissions | Limited likelihood of an international agreement |
| **ETS** | Environmental integrity guaranteed by the cap on emissions | Cost effective: close relation to emissions, time and space flexibility | Poor acceptability for third party operators |
| **Emissions offsetting** | No guarantee of significant abatement | Cost effective: abatement occurs in sectors with low abatement costs | Limited subscription on a voluntary basis |

**Source:* the author, based on (ITF, 2008-18), KiM NITPA (2011), HM Treasury (2011)

∴

Building on these preliminary considerations, this paper will start with a thorough analysis of past emissions abatement achieved in the aviation industry in Part 1. We will try and identify the different fuel use efficiency levies used for achieving such abatement (namely, fleet renewal and technology retrofit on existing aircraft, enhanced airlines operations and improved infrastructure), but also the scale and cost of abatement allowed by each levy. This detailed review of past emissions abatement, based on a cross-analysis of bottom-up and top-down approaches, will lay the ground for the assessment, carried out in Part 2 of this paper, of the potential for future abatement in the aviation sector, be they based on similar fuel use efficiency levies or on other levies which may include air transport demand management (through intermodality for instance) or reduction of jet fuels' carbon content (from the use of alternative fuels). To ensure a better accuracy for this assessment, this paper will focus on mid-term potential for abatement, with 2020 as a main horizon. Combining again top-down and bottom-up approaches, this section will try and draft a marginal abatement cost for $CO_2$ emissions in the aviation industry. Finally, Part 3 will evaluate the impact of the introduction of a price for carbon in the aviation sector. The different options for introducing such a carbon price will be reviewed, with a focus on the specific initiative by the European Union for aviation's inclusion in the existing emissions trading scheme.

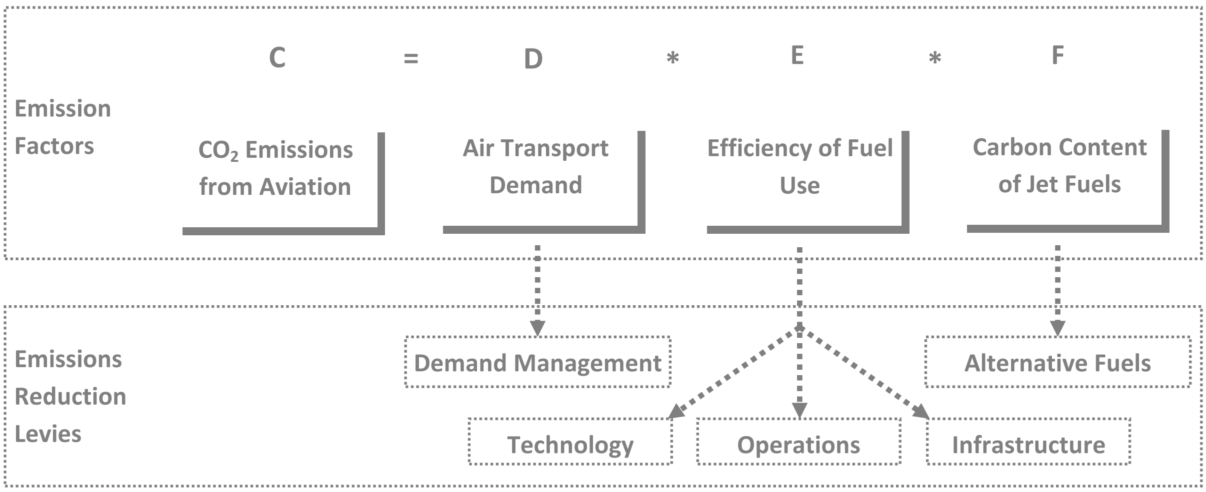
# 1. ANALYSING PAST AVIATION EMISSIONS ABATEMENT

Reviewing and analysing past emissions abatement achieved by the aviation sector in the past is a necessary first step on the way to understanding the challenge that the sector is facing as regards further expected cuts in GHG emissions.

## 1.1 Identifying key pillars for $CO_2$ reduction

Based on the decomposition approach presented in IEA's paper 'The Road from Kyoto' (IEA, 2000) as well as in EuroPIA's White Paper 'Fuelling EU Transport' (EuroPIA, 2011), this paper suggests to characterise the links between air transport, jet fuel use and $CO_2$ emissions using the kind of simplified analytical framework suggested by IEA (see Figure 1), which breaks down aviation's $CO_2$ emissions *C* into the product of air transport demand *D* (measured as passenger-kilometres or tonne-kilometres), efficiency of fuel use *E* (energy used per unit of traffic demand), and the carbon content of jet fuels *F* ($CO_2$ emissions per unit of jet fuel consumed).

**Figure 1 – Methodology for identifying key components of air transport that determine carbon emissions and corresponding levies**




*Source:* the author, based on IEA's methodology (2000)

This methodology suggests there are three main pillars to aviation emission reduction measures.

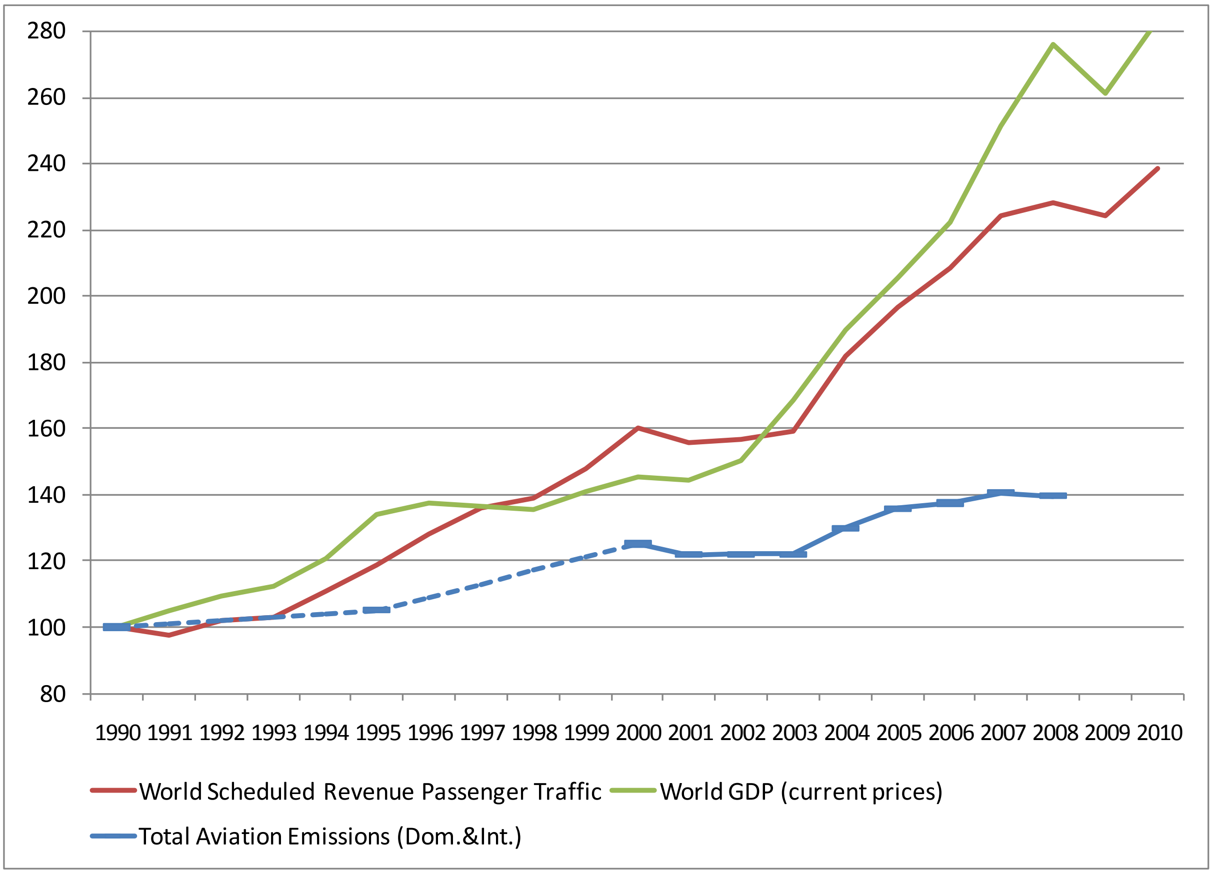
- ∴ Transport demand *(D)* management, through modal shift or network optimisation, can reduce air traffic growth by reducing traffic volume (measured as passengers or tonnes) and/or covered mileage.
- ∴ Optimisation of fuel use efficiency *(E)* can result from progress in aircraft technology (by means of fleet renewal or equipment retrofitting), in airlines' operations (by means of fuel loads optimisation or flight path optimisation), and in airport and air traffic control infrastructure (by means of better connectivity or improved flow management).
- ∴ Reduction of the $CO_2$ content of jet fuels *(F)* depends on developing alternative fuels (e.g. biofuels) certified for aviation use.

As underlined by the IEA, the different components that determine aviation emissions are not necessarily independent of one another. Thus, special attention should be given to potential "rebound effects" that can be observed when measures which are designed to improve efficiency of fuel use lead to a reduction in the cost of travel and, subsequently, to an increase in air transport demand.

## 1.2 Historical emissions: a continued growth trend despite relative decoupling

In the past, $CO_2$ emissions from aviation have increased mainly because of the increase in air traffic demand *(D)*, underpinned by global economy growth trends. Figure 2 illustrates the link between respective evolutions of aviation emissions from fuel use, air transport demand, and world GDP, over a 20-year period from 1990 to 2010.

**Figure 2 – $CO_2$ emissions from aviation, air transport demand and GDP per year, 1990-2010 (1990=100)**




*Source:* Traffic series, given in RPKs (2010 est.), is from ICAO. GDP data, given in current prices, is from IMF. Emissions data are $CO_2$ emissions from fuel use, given in $tCO_2$, from IEA (2010).

Yet historical data reveal a relative decoupling between aviation emissions and traffic, with the elasticity of aviation emissions to traffic increase being less than 0.5. Similarly, the positive values found for the decoupling factor *I*, as defined by the OECD (see OECD, 2002), indicate that the ratio between aviation $CO_2$ emissions and traffic has decreased with time, though more rapidly over the 1900-2000 period ($I_{1990\text{-}2000} \approx 0.27$) than over the 2000-2008 period ($I_{2000\text{-}2008} \approx 0.22$):

$$I_{X-Y}, \textit{decoupling factor over a period from year } X \textit{ to year } Y$$

$$I_{X-Y} = 1 - \frac{Q_Y}{Q_X}$$

$$\textit{where } Q_X \textit{ is the emission intensity for year } X$$

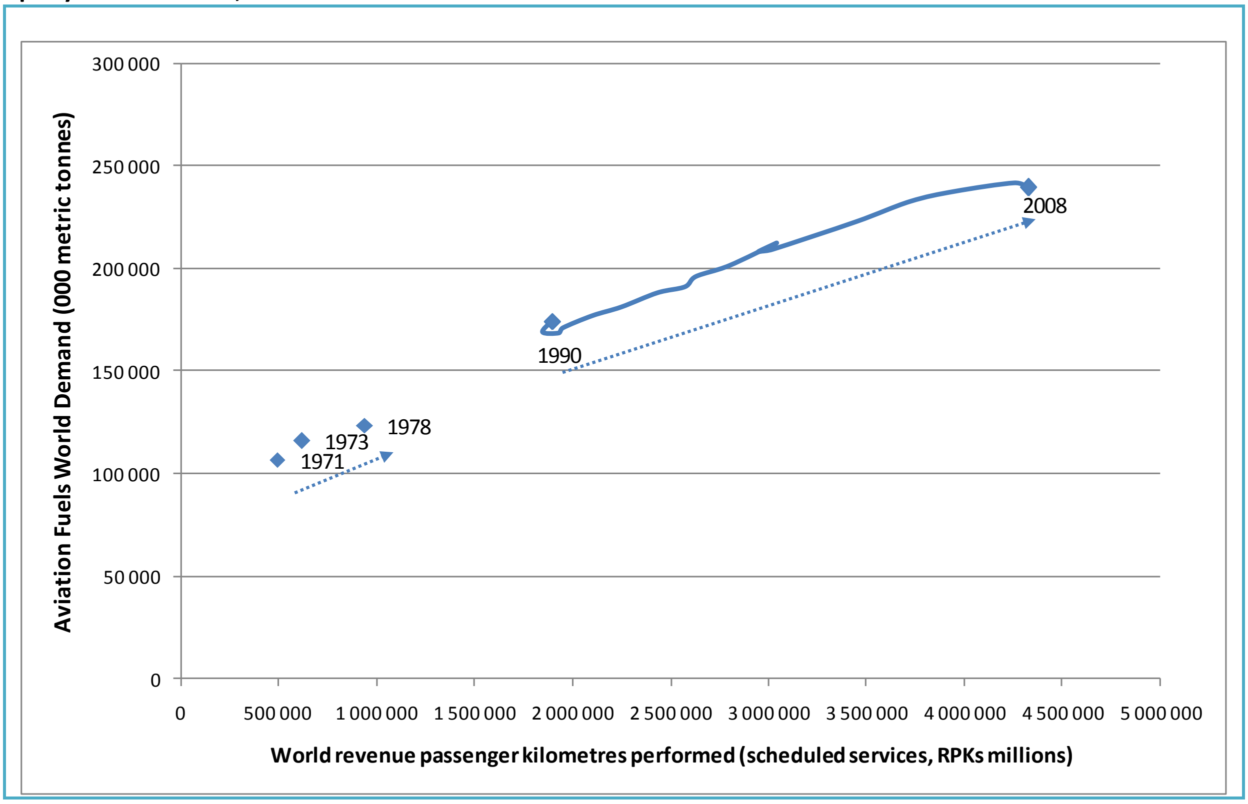
$$Q_X = \frac{CO_2 \textit{ Emissions for year } X}{RPK \textit{ Traffic for year } X}$$

According to the above-mentioned decomposition approach, since no significant change has occurred in the carbon content of conventional jet fuels and no alternative jet fuels (e.g. biofuels) have yet emerged as a large scale solution for aviation supplies, the main driver for the relative decoupling observed between aviation $CO_2$ emissions and traffic growth is to be found in fuel use efficiency gains.

## 1.3 The key drivers to aviation fuel efficiency gains over four decades

Figure 3 illustrates the progressive gains in fuel use efficiency that have been achieved through the past four decades. While scheduled traffic measured as RPKs (revenue passenger-kilometres) was almost 9 times higher in 2008 than in 1971 and almost 2.5 times higher in 2008 than in 1990, jet fuel consumption was only 2.2 and 1.4 times higher respectively over the same periods. Fuel use efficiency has thus increased steadily, showing an almost 75% improvement over the past four decades and still a 40% improvement over the past two decades. Indeed, whereas 0.22 tonnes of jet fuel were consumed per 1,000 RPKs in 1971, the figure decreased to 0.092 tonnes in 1990 and 0.055 tonnes in 2008 for the same volume of traffic carried.

**Figure 3 – Aviation fuels demand per year and revenue passenger kilometres performed on scheduled flights per year worldwide, 1971-2008**



*Source:* Traffic series are from ICAO. Aviation fuels demand compiled from misc. databases and publications by IEA (IEA's *Oil Information* (2009) for years 1971, 1973, 1978, 1990 and 2005 to 2007, author's calculation from IEA's *$CO_2$ emissions from fuel combustion* (2010) for years 2001 to 2004, and 2008) and EIA (for years 1990 to 2007). The graph uses mean values from IEA's and EIA's data series when both are available.

The following breakdown expression for fuel efficiency lays the ground for a first order reasoning on past fuel use efficiency gains in aviation, allowing for a rough assessment of fuel efficiency key drivers' compared impacts over time:

$$Fuel\ Efficiency = \frac{Volume\ of\ jet\ fuel\ burned\ (in\ tonnes)}{\underbrace{Available\ seats * PLF\ (\%)}_{\equiv\ Passengers} * Av.\ Distance\ (in\ Kms)}$$

$$or, on\ a\ first\ order\ approximation\ used\ for\ AAGR\ (\%):$$

$$(Fuel\ Efficiency)_{AAGR} \approx (Fuel\ per\ seat)_{AAGR} - (PLF)_{AAGR} - (Av.Dist.)_{AAGR}$$

This breakdown approach of fuel efficiency echoes the methodology suggested earlier (see Figure 1), which refers to the three sources for fuel efficiency optimisation achievements, namely: aircraft technology, airlines operations or airport and air navigation infrastructure. Here, the fuel per seat results can indeed be interpreted in reference to progress in aircraft technology, while passenger load factor can be taken as one indicator for airlines' operational improvements and average distance would rather refer to a network/infrastructure effect. It should be noticed that several underlying trends of the aviation's industry fast development play a key driver role in airlines' fuel efficiency improvements, namely the growth in average flown distance (defined as the ratio of total passenger-kilometres performed and total number of revenue passengers carried) on the one hand, and in passenger load factor (defined as the ratio of passenger-kilometres performed by the airlines and available seat-kilometres flown) on the other hand:

∴ The growth in average flown distance resulting from the development of long- and very long-haul flights, has a predictable, positive impact on fuel use efficiency. Indeed, overall efficiency is higher on long-haul than short-haul routes for, in particular, take-off and landing flight phases are less efficient than cruise phase. Regarding flown distances, it is worth noticing that ICAO recommends that reporting States use "great circle distances" in all items involving distance computations (see reporting instructions by ICAO in *Air Transport Reporting Form A-S, Traffic-Commercial Carriers-State Totals*). This measurement of distances thus does not take into account distances effectively flown by aircraft, which can be much higher than great circle distances due to air navigation constraints or suboptimal airport procedures for instance.

∴ Second, the industry-wide improvement in load factors, historically resulting from the growing liberalisation of air transport and the progressive development of hub-and-spokes networks, also works mechanically as a key driver for aviation fuel efficiency gains. Indeed, the fuel burned for a given flight is predominantly determined by the aircraft empty weight (including structure, engines, equipments and furnishing, but excluding any luggage, passengers, freight or fuel, empty weight usually accounts for half of aircraft's maximum weight), passengers' weight accounting for a lesser share of fuel consumption. The increase in load factor has a higher impact on the fuel efficiency ratio's denominator (*i.e.* the RPK volume performed) than it has on its numerator (*i.e.* the fuel volume burned).

Table I-1 presents detailed information about the evolutions of aviation traffic and fuel use efficiency across three distinctive periods in aviation history:

∴ The pre-1990 history saw fuel use efficiency gains in aviation of around 4.4% yearly, mainly on account of technological improvements in aircraft, turbines and other equipment. Those technological improvements accounted for a 1.7% yearly decrease in fuel consumption per available seat. Complementary gains were achieved through underlying trends of growing average distances flown (+1.5% per year over two decades) as the result of the development of long- and very long-haul flights) on the one hand, and improving passenger load factors (+1.1% per year) on the other hand.

∴ The 1990s decade still showed great improvement in technology, translating into a 1.4% yearly decrease in fuel consumption per available seat, and average distance flown carried on with a sharp increase (+1.1% per year over the decade). However, aggregated fuel use efficiency gains were lower in that decade than in earlier ones in the absence of consistent progress in passenger load factors over that period (+0.2% per year only, with important variability).

∴ Finally, the 2000s decade kept up to the 1990s overall efficiency gains, with technology still accounting an approximate 1.5% annual decrease in fuel consumption per available seat (in the absence of data for fuel consumption in 2009, this calculation is realised over 9 years only), while the limited growth in average distance flown (+0.3% per year) no longer provided for significant complementary gains. Instead, strong growth in passenger load factors over the decade (around 0.8% per year despite the three major traffic crises of the 9/11 events in 2001, the SARS epidemic in 2003 and the international financial crisis in 2008).

**Table I-1 – Trends in aviation traffic and fuel use efficiency for three distinct periods, 1970-2009**

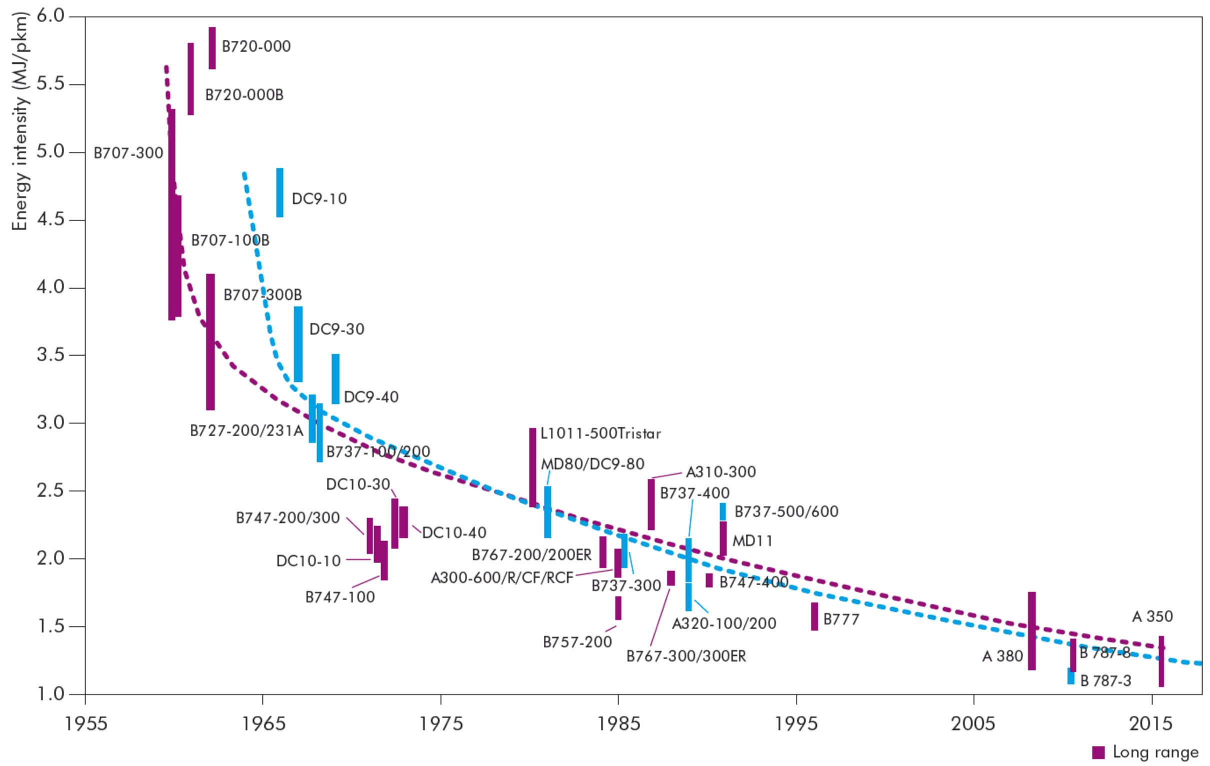
| Period | Traffic (scheduled services) | Fuel use efficiency | |
|---|---|---|---|
| **1970 & 1980s** | 494 bn RPKs in 1971<br>**+7.0% per year;*3.6 overall** | 0.216 tonnes for 1,000 RPKs in 1971<br>**-4.4% per year; -57% overall** | **Fuel per seat ≈ -1.7% per year**<br>**PLF ≈ +1.1% per year**<br>**Av.dist. ≈ +1.5% per year** |
| **1990s** | 1,894 bn RPKs in 1990<br>**+4.0% per year; *1.5 overall** | 0.092 tonnes for 1,000 RPKs in 1990<br>**-2.7% per year; -22% overall** | **Fuel per seat ≈ -1.4% per year**<br>**PLF ≈ +0.2% per year**<br>**Av.dist. ≈ +1.1% per year** |
| **2000s** | 3,038 bn RPKs in 2000<br>**+3,4% per year; *1.4 overall**<br>4,245 bn RPKs in 2009 | 0.070 tonnes for 1,000 RPKs in 2000<br>**-2.9% per year; -18% overall (9 yrs)**<br>0.055 tonnes for 1,000 RPKs in 2008 | **Fuel per seat ≈ -1.5% per year**<br>**PLF ≈ +0.8% per year**<br>**Av.dist. ≈ +0.3% per year** |

*Source:* Traffic series are from ICAO. Fuel use efficiency data calculated using aviation fuels demand compiled from IEA and EIA databases and publications (see Figure 3 for further detail on data selection).

### *a. Technology*

In the light of these preliminary results for fuel efficiency's key drivers' assessment, this paper shall consider first fuel efficiency gains that were achieved by the aviation sector from the technological perspective. Historical trends show that aircraft emissions entering into service today are around 80% more fuel efficient per seat-kilometre flown than they were in the 1960s (ATAG, 2010). These efficiency levels are the result of both step changes – introduction of turbofan engines with increasingly high-bypass ratio for instance – and incremental improvements to aircraft and engine design and operation. As illustrated in Figure 4, the aircraft manufacturing industry has indeed delivered increasingly efficient aircraft.

**Figure 4 – Trends in aircraft efficiency since the early days of commercial aviation, 1955-2015**




*Source:* IEA, 2009 based on Lee, *et al.*, 2009 .

While most of the 20th century saw a race for speed in aviation, increasing nuisance and pollution resulting from the fast development of aviation led to a new search for efficiency from the 1960s on. Introduced in commercial aviation the late 1960s, the high-bypass turbofan was actually the result of this search, and has since delivered a tremendous increase in jet engines' power and a dramatic drop in noise (ATAG, 2010). Improvements in fuel efficiency were thus a by-product of this original search. Aircraft weight reduction achieved through the use of lighter materials or the replacement of former mechanical systems by all-electric systems has also played an important part. Table I-2 presents some major improvements in aircraft and engine technology that have contributed to overall fuel use efficiency gains in aviation.

**Table I-2 – Main technological improvements with regards to fuel use efficiency, 1940-2010**

| | Used technology | Introduction | Efficiency gain achieved |
|---|---|---|---|
| **Engine efficiency** | **Turbopropeller** | 1940s | **25-40%** (compared to turbofan on short haul routes) |
| | **High-bypass ratio turbofan** | 1960s | **1% yearly** since introduction |
| **Aircraft weight reduction** | **Lighter materials** (composite, light aluminium alloys, furnishing, etc.) | 1950s | - |
| | **Carbon braking systems** | 1970s | |
| | **"Fly-by-wire"** (electrical replacing mechanical systems) | 1980s | |
| **Drag reduction** | **Winglets** (available for retrofit) | 1980s | **3-5%** |

*Source:* ATAG, 2010.

Comparing annual fuel consumptions of older and newer aircraft with equivalent seat capacity under similar assumptions for load factor, the IEA assess that a new-generation widebody aircraft, namely the Boeing 747-800 (launch in 2011), might be 22% more fuel efficient than the equivalent widebody aircraft entered into service some 20 years earlier, the Boeing 747-400 (launch in 1989). Similarly, another new-generation widebody aircraft, the Boeing 787 (launch in 2011), which extensively uses composite materials, might be more than 30% more efficient than the equivalent-seating aircraft entered into service 30 years earlier, the Boeing 767 (launch in 1982) (IEA, 2009). Access to airlines operational data on effective fuel burn for several aircraft generations could enable further assessment of emissions abatement that is achievable through fleet renewal. The combination of this data with information on average purchase prices for aircraft (available from *Airline Business* or *Flight Global ACAS Database* sources) could furthermore enable us to determine with good accuracy the cost of emissions abatement using this particular levy.

In view of the gains achieved with each new generation of aircraft, fleet modernisation emerges as a key driver of overall aviation efficiency gains, though the potential for fuel efficiency gains from fleet renewal tends to diminish as current aircraft designs become increasingly optimised. The analysis of past trends in worldwide fleet renewal practices over the last two decades (from ASCEND database) evokes the following comments:

- ∴ The jet fuel price hikes started in 2004 seem to have triggered a concurrent twofold increase in orders backlogs for jet aircraft, from the usual 2700-3300 level (from 1997 to 2004) to 4100 in 2005, 5300 in 2006 and to the 6400-7000 level that has been recorded from 2007 to 2010. In comparison, demand shocks in 1998, 2001 and 2003 had rather led to successive increases in the proportion of available aircraft withdrawn from service to be stored.

- ∴ While the average age of aircraft in service worldwide has consistently increased from 1980 (8.6 years) to 1998 (14.2 years), it has stabilized at 13.0 (+ or – 0.1 year) from 2001 to 2007 before decreasing again to reach a new optimum around 12.6 years, which seems to take into account the latest jet fuel price hikes from 2008.

Further investigation into worldwide fleet management practices could provide a sound basis for an accurate assessment of emissions potential that would be achievable through an acceleration of fleet renewal if such a phenomenon could prove economically viable for airlines.

### *b. Airline operations*

From an operational perspective, the principles underlying past improvements in airlines' fuel use efficiency are more difficult to grasp, for they have varied considerably at different times. Firstly, the 1970s and 1980s will not be analysed in detail from the airlines' operational perspective for there is insufficient operational or financial data for that period on the one hand, and for airlines at that time often enjoyed monopoly positions in their respective national markets, with little incentive to seek improvements in fuel efficiency on the other hand.

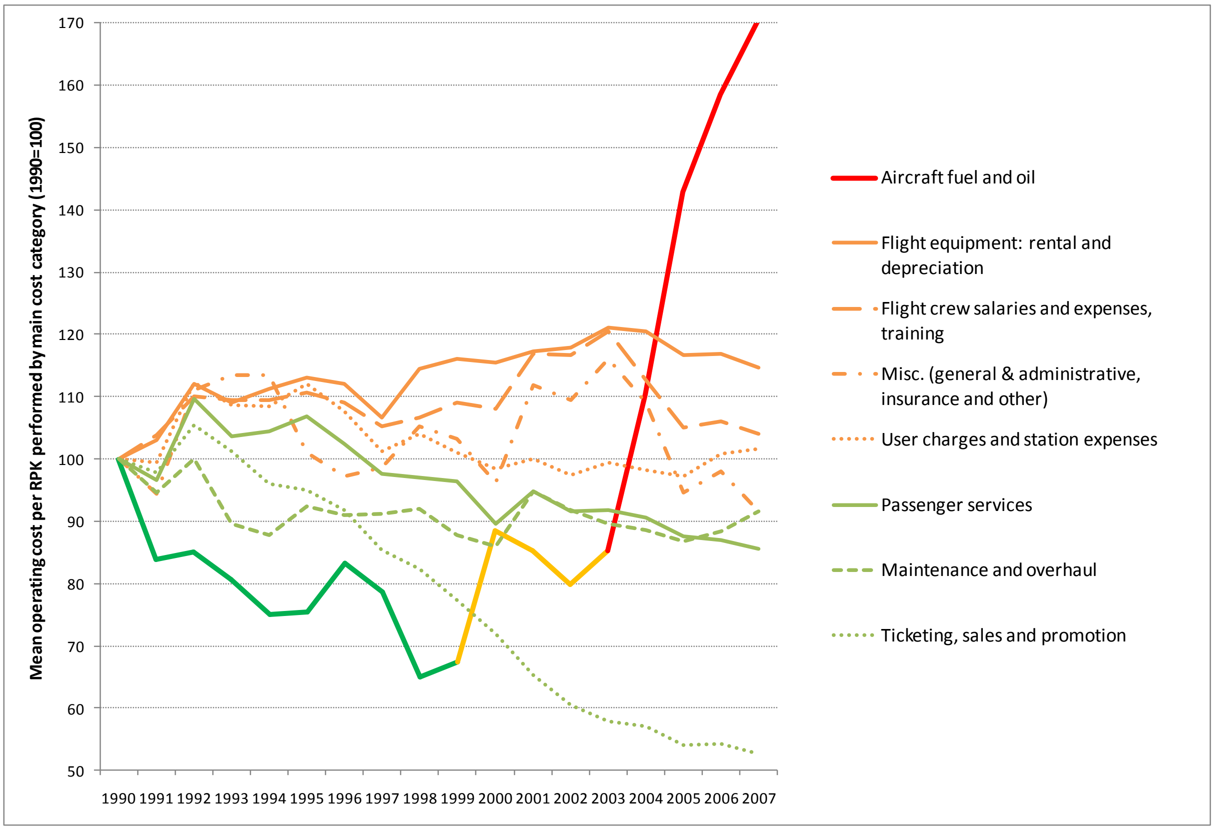
Conversely, the 1990s saw the beginning of liberalisation in air transport and aviation-related services (handling, maintenance, air navigation, among others) as well as products (with the rise of new manufacturers and parts providers). Airlines began the decade with five consecutive years of net losses, resulting in the first real attempts by the industry to cut costs (see Table I-3). The eight-month hike of the jet fuel barrel price above the $25 level (from August 1990 to March 1991), with a peak value around $63 in October 1990, which occurred in the unfavourable conjuncture of the Gulf War and of the global recession, did not lead to any major changes in airlines' fuel costs management though it was partly responsible for those losses. Indeed, except for this event, the 1990s was largely characterised by reasonably low fuel prices (most commonly between $15 and $25 per barrel) and a rather low share of fuel in airlines' overall operating expenses (most commonly between 11% and 13%, usually ranking 4th in airlines' main categories of operational expenses)[1]. As a result, airlines had no great incentive to focus on reducing fuel costs. Instead, they attempted to cut costs in three main cost categories: *i)* commercial activities (ticketing, sales and promotion), *ii)* maintenance and overhaul, and *iii)* services to passengers (see Figure 5). Interestingly enough, those cost categories for which airlines achieved unitary gains in the 1990s concerned areas progressively being liberalised; in particular, airlines increasingly arbitrated between self-providing and outsourcing those services. Fuel use efficiency gains that were achieved during that decade thus still resulted mainly from technological improvements in aircraft and aircraft equipment rather than from a fuel-driven optimisation of airline operations.

**Table I-3 – World airlines' financial results (profits and losses after income tax, $US millions), 1990-2009**

| | | | |
|---|---|---|---|
| **1990-94 (accumulated)** | | **-20 500** | |
| **1995-99 (accumulated)** | | **35 050** | |
| ***2000*** | *3,700* | ***2005*** | *-4,100* |
| ***2001*** | *-13,000* | ***2006*** | *4,990* |
| ***2002*** | *-11,300* | ***2007*** | *14,529* |
| ***2003*** | *-7,560* | ***2008*** | *-36,000* |
| ***2004*** | *-5,670* | ***2009*** | *-9,900* |
| **2000-09 (accumulated)** | | **-64 311** | |

*Source:* Financial data are from ICAO for years 1990 to 2007 and from IATA for years 2008 and 2009.

**Figure 5 – Evolution of airlines' mean operating costs by main cost category, 1990-2007**




Green curves are for categories which saw unitary gains over the 1990s decade, namely: a) ticketing, sales and

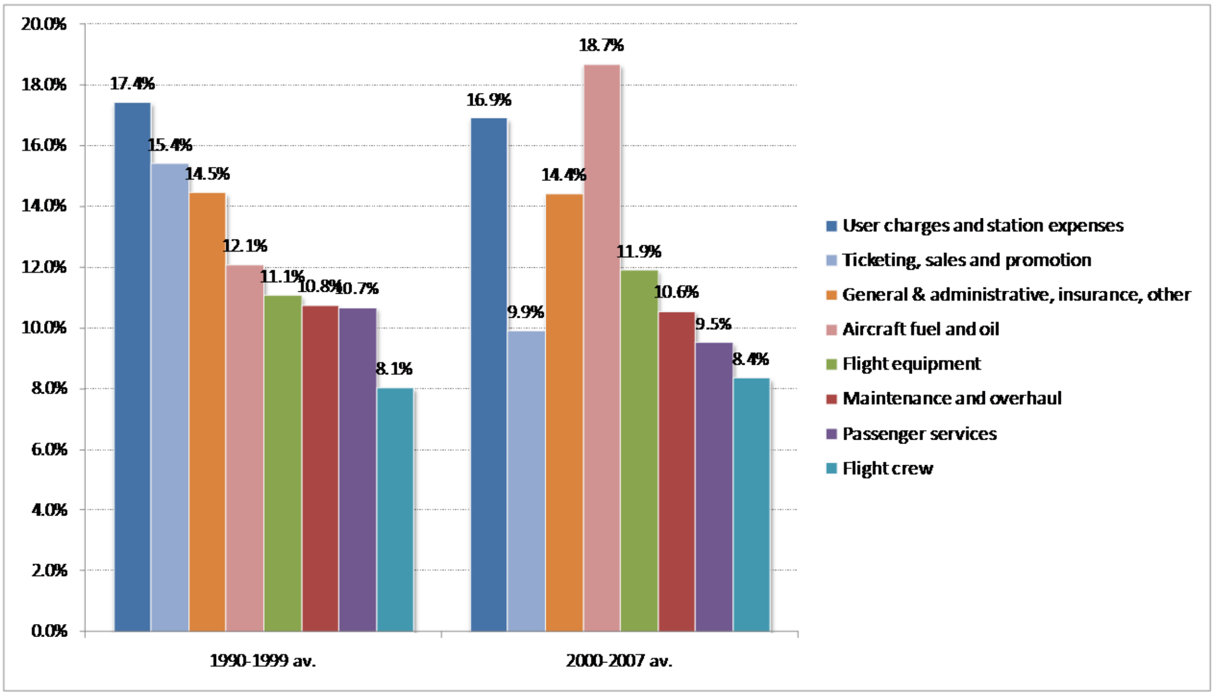
[1] For details about the methodology used to breakdown of operational expenses based on ICAO's airlines financial data, see Appendix 2. For details about jet fuel prices historical evolution, see Appendix 2.

promotion, b) maintenance and overhaul, and c) passenger services.

*Source:* Airlines' financial and traffic data are from ICAO.

In fact, the year 2000 was the first time in aviation history that fuel occupied the number two position in airlines' main categories of operational expenses, following the sharp increase in jet fuel prices from less than $14 per barrel in February 1999 to more than $41 in January 2000. Except for a ten-month period following 9/11 events, jet fuel prices have remained consistently above the $30 threshold over the 2000s and above the $40 threshold since 2004. Fuel cost then became airlines' highest cost category, which it has remained so far (see Figure 6). In this context, the heavy losses recorded by airlines following the severe crises of the century's first decade (the 9/11 events in 2001, the SARS epidemic in 2003 and the international financial crisis in 2008) laid the ground for a more dynamic optimisation of their operations as regards fuel consumption. The 2000s is therefore analysed hereinafter in more details as it provides interesting material for an *ex post* analysis of fuel use efficiency improvements that are achievable through the optimisation of airlines' operations with reference to a strong fuel price signal.

**Figure 6 – Share of fuel in airlines' main cost categories over two periods of time, 1990-1999 and 2000-2007**




*Source:* Airlines' financial data are from ICAO.

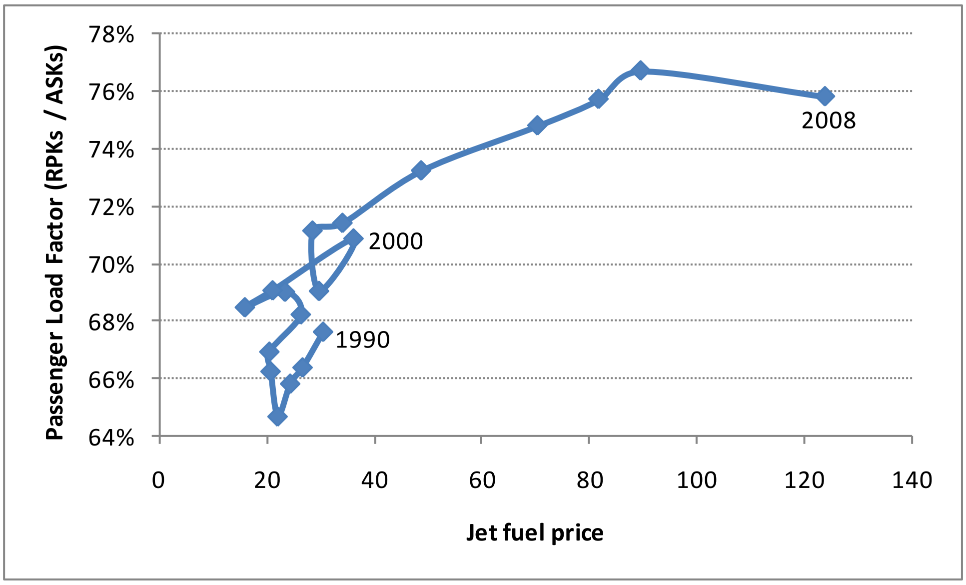
According to airlines' associations (see ATA and IATA websites), airlines have sought fuel efficiency improvements in their operational practices over the last decade through an extensive set of actions. In particular:

∴ First, airlines focused on implementing operational procedures with short-term returns, and having negative costs in most cases, e.g. single-engine taxiing, selective engine shutdown during ground delays, weight-reduction programs, optimisation of fuel loads (to reduce the cost of carrying extra fuel), optimisation of flight planning (to incorporate the most efficient routes and altitudes), reduction of thrust at takeoff, reduction of inefficient low-altitude manoeuvring, or minimisation of auxiliary power units usage (by using airport electrical power on the ground). Many of those procedures and techniques had been experimented for years in the United States due to more stringent local regulation on nitrous oxide emissions on airports.

∴ Airlines also initiated mid-term operational optimisation programs including the redesign of hubs and schedules (to minimise congestion), further improvement in airplanes' load factors (through reduction of overcapacity, optimised yield management and overbooking) and the pooling of resources through alliances (to optimise load factors, besides purchasing supplies and services in bulk). Those measures, though not easily achievable in the very short-term since they require modifications to airlines' planning of network, fleet, purchase and sales, might however turn out to be cost negative.

Since it is difficult to assess the individual impacts of these actions, we shall examine the correlation between the sharp rise in fuel prices in the 2000s and the intensification of fuel efficiency efforts by airlines over that period from the angle of the passenger load factor indicator. In this respect, Figure 7 illustrates the consistent progress made by airlines alongside the increase in jet fuel prices in the 2000s, the only exception to this trend being the 2008 demand crisis. The decade-average passenger load factor increased exactly by 2 percentage points in the 1990s compared to the 1980s (from 65.3% to 67.3%) and by 6 more percentage points in the 2000s compared to the 1990s (from 67.3% to 73.5%). Though further progress can probably still be achieved in this area, load factor levels that have been recorded in the 2000s might be close to a realistic operational maximum considering some of air transport's characteristics, such as its uneven repartition across seasons, or its fluctuant directional distribution on some routes.

**Figure 7 – Evolution of world airlines' passenger load factor for scheduled services in relation to jet fuel price evolution, 1990-2008**




*Source:* Passenger traffic and capacity data are from ICAO, jet fuel price data series are from EIA and Platt's. For more details about jet fuel price data series used in this paper, see Appendix 3.

### c. *Airport and air navigation infrastructures*

Finally, from the infrastructure perspective, the inefficiencies that have been brought to light by the strong growth trends over the past decades are deemed to weigh more and more on the environmental and economic performance of the sector unless modernisation programmes, both for technology and operational procedures, can impulse improvements in this regard.

First, it is interesting to note that air navigation – also referred to as air traffic management – is usually considered, in the same way as airports, to be an essential infrastructure to air transport, an infrastructure made of systems, people and procedures which enable the sector to operate in a safe and efficient manner (SESAR, 2006). Since the 1940s, air traffic has been managed by routing aircraft into narrow, predetermined routes designed according to the domestic airspace requirements of countries on the one hand, and to the location of ground-based navigation aids on the other hand. This and the division of airspace into segmented control sectors, have resulted in an artificial increase in flown distance as compared to the shortest route determined by the "great circle distance", equivalent in the air of the so-called "straight line" on the ground. Other infrastructural constraints to an optimal flow management of aircraft in the airspace consist, for instance, in rules of minimum horizontal separation distance (from 5 to 50 nautical miles depending on airspaces and radar equipment) or minimum vertical separation distance (1,000 or 2,000 feet) between two aircraft.

As already mentioned, infrastructure efficiency can't be directly characterised from available statistics that refer to flown distances (or revenue passenger-kilometres performed or revenue tonne-kilometres flown) because those statistics are actually calculated based on theoretical flightpaths ("great circle distances") that do not reflect additional distances flown on account of air navigation constraints or airport procedures for instance. So, in a way, the relative efficiency of air transport infrastructure is "internalised" in air transport fuel use efficiency measures presented hereinafter. As will be shown in Part 2, modernisation programmes are under way to tackle infrastructure-related inefficiencies in the air transport sector. However, most of these programmes have a quite recent history for the sector primarily focused on developing infrastructure fast enough to accommodate its strong activity growth until the early 2000s. Infrastructure-related fuel use efficiency gains have indeed emerged as an essential challenge to take up, along with the first truly critical occurrences of capacity saturation in the US and in Europe, in the last decade. The benefits to expect from large-scale infrastructure modernisation programmes might thus be among the main stakes for aviation's sustainable development over the next decades.

## 1.4 Assessing past emissions abatement from three fuel efficiency levies

For the purpose of assessing the overall fuel consumption abatement (and corresponding $CO_2$ emissions abatement) achieved in the aviation sector, we will consider the following calculation of aviation fuel consumption:

$$Fuel\ Demand \ = \ Traffic\ (in\ RPK) \ * \ Fuel\ Efficiency\ (in\ tonnes\ per\ RPK)$$

Based on this definition of fuel demand, a baseline scenario for 2000-09 fuel consumption and $CO_2$ emissions can be defined by projecting fuel efficiency trends observed in the 1990s onto the traffic performed in the 2000s, using a linear regression method (see Table I-4). A first baseline scenario is drawn using the fuel efficiency gains of the whole 1990-99 decade ($R^2$ determination coefficient for linear regression over that period is 0.971). Maximum $R^2$ determination coefficient is actually found for the 1992-99 period ($R^2$ = 0.992), which will be used as an alternate baseline scenario (thereafter referred to as High Baseline Scenario, as opposed to 1990-99 which will be the Low Baseline Scenario).

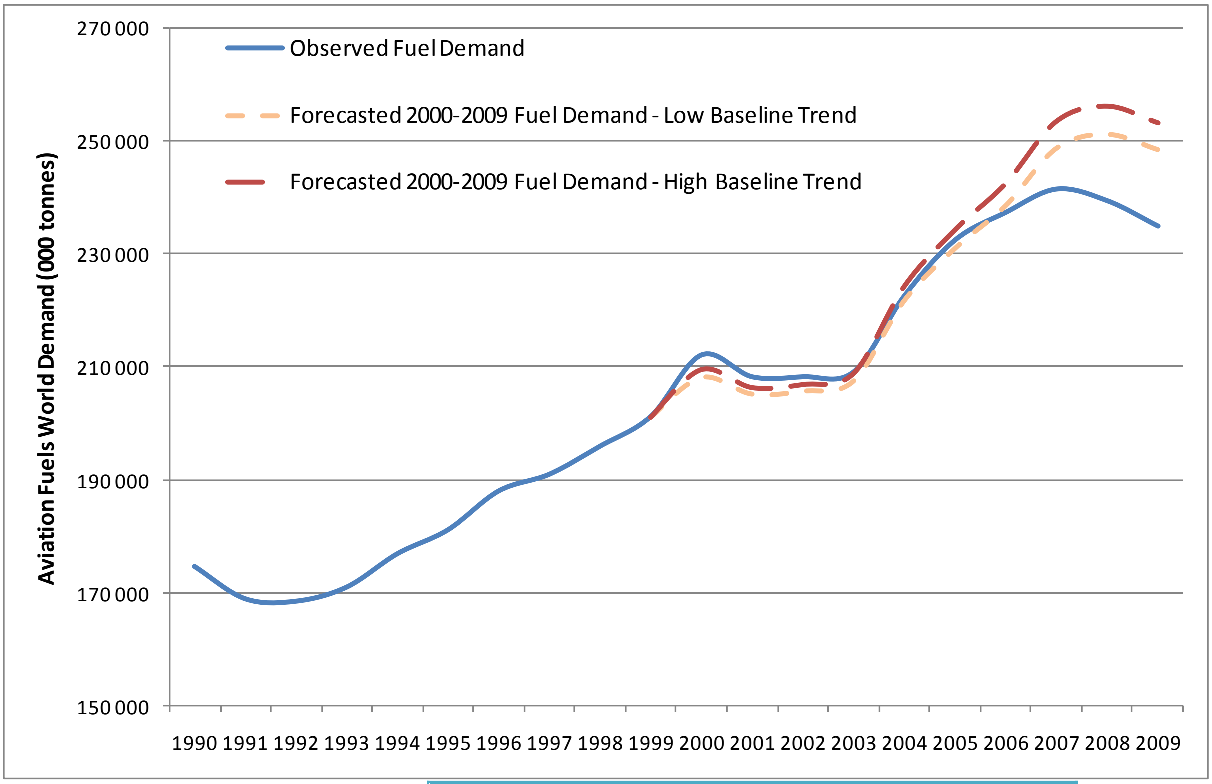
**Table I-4 – Linear regressions used for linking aviation fuels demand (in 000 tonnes) to traffic (in RPK millions) in baseline scenario**

| Reference Period | Linear Regression Characteristics Constant | Traffic Variable Coefficient | $R^2$ Coefficient |
|---|---|---|---|
| **1990-99** | 107,001 | 0.0334 | 0.971 |
| **1992-99** | 99,864 | 0.0362 | 0.992 |

*Source:* Traffic series are from ICAO. Fuel use efficiency data calculated using aviation fuels demand compiled from IEA and EIA databases and publications (see Figure 3 for further detail on data compilation).

Fuel efficiency improvements that were achieved in the 2000s decade thus appear to have allowed for yearly fuel demand to be 5% to 7% lower in 2009 than forecasted through the baselines scenarios drawn from the 1990s trends. Fuel consumption abatement over the 2000s decade can be estimated between 21 and 50 million tonnes of jet fuel worldwide, which translates into 65 to 158 million tonnes of $CO_2$ abated over ten years, compared to baseline scenarios.

**Figure 8 – Impact assessment of the change in trends in aviation fuel efficiency between two decades**




| | Difference from Forecast to Observation over 2000-2009 Fuel Demand | $CO_2$ Emissions |
|---|---|---|
| **Low Scenario Trend** | -20.8 M tonnes | -65.3 M tonnes |
| **High Scenario Trend** | -50.2 M tonnes | -157.7 M tonnes |

*Source:* Traffic series are from ICAO. Aviation fuels demand compiled from misc. databases and publications by IEA (IEA's *Oil Information* (2009) for years 1971, 1973, 1978, 1990 and 2005 to 2007, author's calculation from IEA's *$CO_2$ emissions from fuel combustion* (2010) for years 2001 to 2004, and 2008) and EIA (for years 1990 to 2007). The graph uses mean values from IEA's and EIA's data series when both are available.

To further analyse the respective effects of fuel efficiency gains from *i)* technological improvements in the fleet, *ii)* improvements in load factors, and *iii)* growth in average distance flown, it is suggested to use the previously mentioned breakdown approach to fuel efficiency gains in the forecasting process. The beginning of the 1990s decade being strongly influenced by the world economic crisis and the impact of the Gulf War, the 1992-99 period will be privileged as a reference for ulterior forecasts (hereinabove called High Baseline scenario). For further reference, fuel efficiency indicators for that period are estimated to be as follows: a 1.2% yearly decrease in fuel burn per available seat, a 0.9% yearly increase in average flown distance, and finally a 0.7% yearly increase in passenger load factor (with yearly variations from -1.7% to +2.4%). Overall, yearly fuel efficiency gains were around 2.7%, as they were for the whole decade. Three successive forecast will thus be realised by means of linear regressions for a step-by-step breakdown of fuel efficiency gains over the 2000s decade as compared to the High Baseline scenario. Table I-5 presents the methodology and results for this decomposition of fuel efficiency gains in the Low Baseline and High Baseline scenarios. These results show a significant sensitivity to the choice of the reference period, for individual efficiency gains from technology, seats occupancy and distance are quite different when considered over the 1990-99 decade or over the period 1992-99.

**Table I-5 – Cumulative effects of technology, distance and load factor on fuel efficiency gains in the 2000s, compared to the High Baseline scenario (with 1992-99 trends)**

| Regression steps | Measured effects (average annual growth rates) | Fuel use efficiency gains over 2000-09 compared to baseline scenario |
|---|---|---|
| $\frac{Fuel\ burn}{Seats}$ ($R^2$=0.995) | Technological gains: -1.5% vs. -1.2% | ≈ 9.5 Mtonnes jet fuel<br>≈ 30 Mtonnes $CO_2$ |
| $\frac{Fuel\ burn}{Seats * Km}$ ($R^2$=0.996) | Technological gains: -1.5% vs. -1.2%<br>Average distance growth: +0.3% vs. +0.9% | ≈ 6.4 Mtonnes jet fuel<br>≈ 20 Mtonnes $CO_2$ |
| $\frac{Fuel\ burn}{Seats * Km * PLF}$ ($R^2$=0.992) | Technological gains: -1.5% vs. -1.2%<br>Average distance growth: +0.3% vs. +0.9%<br>Load factor increase: +0.8% vs. +0.7% | ≈ 50.2 Mtonnes jet fuel<br>≈ 158 Mtonnes $CO_2$ |

*Source:* Traffic series are from ICAO. Fuel use efficiency data calculated using aviation fuels demand compiled from IEA and EIA databases and publications (see Figure 3 for further detail on data selection).

We find here the confirmation of the high responsiveness of overall fuel efficiency in the aviation sector to technological improvements, as well as of the predominant impact on relative efficiency gains of intensified efforts by the airlines to improve passenger load factors in the 2000s as compared to the previous decade. Notwithstanding the adverse effect of the relative deceleration in average distances increase over this decade, improvements in technology and in passenger load factors are assessed to be responsible for, respectively, around 20% and 80% of jet fuel consumption abatement and emissions abatement over the decade as compared to the baseline.

These results however call for a set of comments as to the potential replication of past fuel use efficiency gains in the future:

∴ First, concerning the effect of average flown distances on aviation fuel efficiency, it can be usefully noted that the relative slowdown in average flown distance increase in the 2000s as compared to previous decades can be accounted for by two combined factors: *i)* a higher impact of 2001 (9/11 events) and 2003 (SARS epidemic) air transport crises on the long-haul flights than on the short-haul, and *ii)* the particularly strong momentum of low-cost carriers in Europe and Asia at that time, which networks are mainly focused on short- to medium-haul routes. While the first factor might remain linked to air transport conjuncture, the second factor might have a consistent effect on the average growth of average flown distance in the future. Indeed, while average distances started to grow again at a significant pace in 2003 after the crises, the average annual growth rate has remained around 0.7% over the end of the decade, compared to 1.5% in the 1970-1980s and 1.1% in the 1990s.

∴ Besides, concerning abatement achieved by airlines through improvements in operations aiming at increasing their passenger load factors, it comes intuitively that airlines' efforts in this regard come at a negative cost. Indeed, assuming for instance that traffic (as measured in RPKs) remains unchanged, a 1% increase in passenger load factor for a given year has to result from an approximately 1% decrease in capacity in this year, as measured in available seat-kilometres. Thus, such an improvement in load factor, while having no impact on the airline's revenues (since traffic is unchanged), can be assessed to have a positive impact on the airline's balance sheet through a decrease in operating expenses that are directly related to capacity. Assuming there is no change in the fleet age, configuration or technological performance, nor in the average distance flown, a 1% decrease in capacity can be translated in proportional cost savings on the following expenses: *i)* user charges and station expenses, *ii)* maintenance and overhaul, *iii)* flight equipment, *iv)* flight crew salaries and expenses, and *v)* aircraft fuel and oil. Using this simplified calculation method, when confronting savings in operational expenses on the one hand, and tonnes of jet fuel abated through the 1% decrease in capacity on the other hand for a sample of years from 1990 to 2007, it appears that total operational cost savings amount to between three and six times the sole cost savings linked to the reduction in fuel burn, with total cost savings ranging from 940$ to 1,420$ per tonne of fuel abated, which would be equivalent to a negative cost of abatement for $C0_2$ emissions ranging from -450$ to -300$ per tonne. This kind of cost savings would represent such high, immediate financial gains that one might guess that, while there might be a significant potential for fuel efficiency gains from the improvement of passenger load factors by airlines, some practical constraints are likely to interfere and actually increase the cost of these measures for airlines. Indeed, even in the most mature aviation markets, the learning curves of network optimisation as well as capacity and yield management have resulted in a very progressive increase in passenger load factors. So it has been the case in the United States, from levels of 70% in the late 1990s to record levels of nearly 82% in 2010. Individual market players elsewhere have also achieved similar passenger load factors performances. In Europe indeed, consolidated European carriers such as Air France-KLM, or low-cost carriers such as Ryanair and easyJet, have recorded that kind of performance levels lately (respectively 83%, 82% and 87% in 2010). However, other airlines, though equally performance-oriented and cost-sensitive (e.g. Lufthansa, British Airways), still record load factors no higher than the world average.

# 2. ASSESSING AVIATION EMISSIONS ABATEMENT POTENTIAL FOR THE FUTURE

Understanding the dynamics of past fuel use efficiency measures in the aviation sector is a first step on the way to assessing future potential in that regard. However, it appears that future GHG emission reduction that will be achieved by the sector will pertain to all three pillars of emissions reduction measures, namely transport demand management, optimisation of fuel use efficiency and reduction of the jet fuels' carbon content. Faced with an increased pressure to mitigate aviation's impact on climate change, the actors of the aviation ecosystem are likely to consider the whole range of levies that have been identified for emission abatement. Their arbitration among those levies will depend on several environmental and economic criteria, which leads us to emphasize in this second part both the abatement potential and the abatement cost from each levy.

## 2.1 Abatement potential from traffic demand management

As far as demand management levies are concerned, very few countries seem to have access to relevant tools and resources and/or to have identified these levies as essential contributors to emission reduction effort in the transport sector as a whole and in aviation in particular. The European Commission claims it will implement a competitive and resource-efficient multimodal transport system by 2050 which could encourage modal shift from aviation to rail. The EC foresees the completion of the European high-speed rail network by 2050 and the tripling of the size of the existing network (from 10,000 km to 30,000 km of track) by 2030, with significant effort put into the improvement of linkages between the various transport networks. For instance, high-speed rail could offer a better alternative to aviation for journeys up to 3-4 hours, and the majority of medium-distance passenger transport could go by rail by 2050, with high-speed rail outpacing the increase in aviation for journeys up to 1,000 km (EC, 2011b).

Such a scenario unquestionably leads to a relative reduction in aviation $CO_2$ emissions compared to baseline scenarios without modal shift. However, in the framework of this study, the lack of access to traffic and cost data for this European plan for a single transport system, as well as for any other potential similar plan in other parts of the world, has hindered further assessment of the potential emissions abatement achievable through this levy, as well as of the corresponding costs. It is worth noticing however that demand management levies in certain countries may require to pay due care to potential modal shift of passengers or goods from aviation to other modes of transport with questionable environmental performances, such as diesel-powered trains.

## 2.2 Abatement potential from fuel use efficiency

As already mentioned in Part 1 of this paper, optimisation of fuel use efficiency is an important levy in the sector's overall emissions reduction effort. It has been well exploited in recent years under rising pressure on the jet fuel price front, but could provide significant further gains by 2020.

### *a. Technology*

A direct way for aviation to improve its overall fuel efficiency is fleet modernisation through renewal and retrofit. Fleet renewal is a complex phenomenon to apprehend at a global level since less fuel efficient aircraft that are replaced by more fuel efficient ones in an airline fleet are likely to be sold to another airline that would need to develop with low capital expenditure for instance. Further investigation into the world fleet's historical structure and management dynamics (e.g. evolution of the average age of aircraft in service, changes in aircraft ownership along its lifetime, changes in aircraft usage, as well as storage and retirement practices) could provide a better understanding of fleet management practices worldwide. Such understanding is necessary to determine whether the acceleration of fleet renewal (by means of early retirement of older aircraft and their replacement by newer ones) could provide new potential for emissions abatement and, if so, at what cost to the airlines.

According to Airbus and Boeing, about 25,000 passenger aircraft, valued at more than $2.9 trillion, are expected to be delivered in the next 20 years. Ten thousand of these aircraft will replace older, less fuel efficient aircraft, as part of standard fleet renewal practices; some additional 15,000 aircraft will be delivered to meet the world's growing need for mobility by air. It means the world's fleet will total about 29,000 in 2030. Many of these might be whole new design aircraft. This represents a great deal of emissions reduction potential in the medium- to long-term.

Working at the individual airline level, fleet renewal and retrofit are one of the most direct ways to improve fuel efficiency. Table II-1 by IATA shows that anticipated abatement in $CO_2$ emissions from technology improvements in aircraft designs through fleet renewal and retrofits could reach 25 to a 35% fuel efficiency gain per seat-kilometre by 2020 and to a further reduction potential beyond 2020.

**Table II-1 – $CO_2$ reduction options from technology improvements on a baseline aircraft**

| Timelines and examples of technologies | Impact |
|---|---|
| **Retrofits** | **7-13%** |
| • Winglets mounted on the wingtips of aircraft improve aerodynamics and reduce fuel burn | |
| • More advanced engine components for better combustion and airflow | |
| • Lighter materials for furnishing in the cabin | |
| • Less energy-consuming lighting and in-flight entertainment | |
| **Production Updates** | **7-18%** |
| • More airframe structure components made of lightweight composite material instead of aluminium | |
| • Advanced engines for current aircraft production series | |
| **New aircraft design before 2020** | **25-35%** |
| • Geared turbofan engine will reduce fuel burn 10-15% | |
| • Open rotor engine will reduce fuel burn around 25% | |
| • Counter-rotating fan will reduce fuel burn 10-15% | |
| • Advanced turbofan will reduce fuel burn around 15% | |
| • Laminar flow reduces aerodynamic drag by reducing turbulence on aircraft surface, 10-15% less fuel burn | |
| **New aircraft design after 2020** | **25-50%** |
| • Blended wing body, rather than the classical tube-and-wing architecture | |
| • Revolutionary engine architectures | |
| • Fuel cell system for on-board energy | |

*Source:* IATA, *A global approach to reducing aviation emissions*, November 2009.

According to the European Petroleum Industry Association (Europia, 2011), on a lifetime basis cost assessment, implementing such energy efficiency measures as listed by IATA could have low or even negative $CO_2$ abatement costs.

In the IATA 'Technology Roadmap Report' (IATA, 2009b), the industry has conducted a detailed assessment of potential fuel burn reduction through retrofit on existing aircraft, and of the corresponding costs. For a baseline aircraft featuring 120 seats, with approximate takeoff gross weight of 60 tonnes an fuel capacity of 24,000 litres, IATA has assessed the results from 16 possible airframe technologies retrofits (ranging from composite secondary structures to lithium batteries for secondary power, as well as blended winglet, all of these technologies being characterised by their respective readiness level) as well as from engine retrofits. Taking IATA's results for the baseline aircraft as a reference for systemwide potential improvements from technological retrofits on the existing fleet (around 24,000 aircraft, according to ICAO), and assuming *i)* a 10% aircraft fleet retrofit rate yearly from 2010 to 2019, *ii)* a 1.2% yearly increase in global aviation fuel burn by 2020 (calculated from a 4% increase in RPK traffic and a 0.22 decoupling factor over the decade, equal to $I_{2000\text{-}2008}$ which was calculated in section 1), *iii)* a constant $85 jet fuel price per barrel (in 2008$), and *iv)* a 10% discount rate, the potential for abatement from the 17 identified retrofit technologies and their respective costs is presented in Table II-2. Abatement potentials are assessed from "technology pessimistic" approach, which takes into account the low-end of the fuel burn reduction range presented by IATA. As for abatement costs, they are assessed based on a median retrofit technology cost, calculated as the simple average of minimum and maximum costs displayed by  for each retrofit technology.

**Table II-2 – Abatement potential and costs from 17 airframe and engines retrofit technologies on the world aircraft fleet by 2020**

| Technology | Minimum fuel burn reduction | Estimated retrofit costs (US$ million) | | | $CO_2$ abatement by 2020 (Mtonnes) | Abatement cost by 2020 (2008$/t$CO_2$) |
|---|---|---|---|---|---|---|
| | | *min* | *max* | median | | |
| **AR6 Lithium batteries for secondary power** | 0.1% | *0* | *0.01* | 0.005 | 4.6 | -198 |
| **AR12 Drag reduction coatings** | 0.1% | *0* | *0.01* | 0.005 | 4.6 | -198 |
| **AR9 Aircraft graphite films** | 1.0% | *0.01* | *0.1* | 0.055 | 45.7 | -197 |
| **AR10 Zonal dryer** | 1.0% | *0.01* | *0.1* | 0.055 | 45.7 | -197 |
| **AR1 Composite secondary structures** | 1.0% | *0.1* | *1.0* | 0.55 | 45.7 | -52 |
| **AR15 High power LEDs for cabin lighting** | 0.1% | *0.01* | *0.1* | 0.055 | 4.6 | -52 |
| **AR3 Raked wingtip** | 3.0% | *1* | *10* | 5.5 | 137.1 | 325 |
| **AR4 Blended winglet** | 3.0% | *1* | *10* | 5.5 | 137.1 | 325 |
| **AR2 Wingtip fence** | 1.0% | *1* | *10* | 5.5 | 45.7 | 1,400 |
| **AR5 More efficient gas turbine APU** | 1.0% | *1* | *10* | 5.5 | 45.7 | 1,400 |
| **AR7 Variable camber with existing control surfaces** | 1.0% | *1* | *10* | 5.5 | 45.7 | 1,400 |
| **AR8 High strength glass microspheres** | 1.0% | *1* | *10* | 5.5 | 45.7 | 1,400 |
| **AR11 Riblets** | 1.0% | *1* | *10* | 5.5 | 45.7 | 1,400 |
| **AR13 Landing gear drive** | 0.1% | *0.1* | *1.0* | 0.55 | 4.6 | 1,400 |
| **AR14 Wireless optical connections for in-flight entertainment** | 0.1% | *0.1* | *1.0* | 0.55 | 4.6 | 1,400 |
| **ER Engine retrofits** | 1.0% | *1* | *10* | 5.5 | 45.7 | 1,400 |
| **AR16 Fluoropolymers** | 0.1% | *1* | *10* | 5.5 | 4.6 | 15,921 |

*Source:* the author, from IATA, *Technology Roadmap Report*, 2009.

Based on these assumptions, taking only technology retrofits with negative-cost abatement into account (AR6, AR12, AR9, AR10, AR1 and AR15), world fleet's retrofits would provide a 3% fuel burn reduction in 2019 and an overall 2% reduction in fuel burn over the 2010-19 decade (151 million tonnes of $CO_2$). The 7-13% range presented in Table II-1 could only be achieved if technology retrofits involving an abatement cost above $300/tonne $CO_2$ (AR3 and AR4) were largely deployed.

It can be noted that incremental gains achieved through technological retrofits on existing aircraft interfere with usual fleet renewal practices for they make it less economical to accelerate replacement of older aircraft by more recent, environment-friendly aircraft. Based on this observation, the sector is sometimes accused of "specification creep", favouring minor advances that forever delay the emerging of radical new designs. Huge development costs involved when developing a new model (around $10 billion for a narrowbody model for instance) are key factors in this arbitrage.

### b. Operations

As already mentioned, incremental progress in terms of optimising airlines' passenger load factors might still be achievable. However the fact that airlines could be reaching an operational optimum in some mature markets around 80-85%, might make emissions abatement from this levy much more expensive in the future due to additional costs in overbooking management, planning and network optimisation information systems, etc. New improvements could still be achieved in some markets such as low-cost, short-haul travel since airlines such as Ryanair are trying to get new seating configurations certified by aviation safety authorities in order to increase capacity of current aircraft by allowing passengers to stand up through the flight.

Other operational improvements might come from further progress made by airlines along their weight reduction action plans. New seats designs for instance could provide up to 40% gain in total seats weight (translating into the abatement of up to 5,200 tonnes of $CO_2$ per year for Air France's narrowbody fleet).

However, due to the lack of data on the extent and cost of further fuel use efficiency gains that shall be achieved from the operational perspective, this paper will not provide a detailed assessment of this specific emission reduction levy.

### c. Infrastructure

Introducing more flexibility in the management of aircraft flows to exploit prevailing weather and traffic conditions (e.g. streams and tail-winds), achieving more airspace capacity to reduce ATC-related delays, resorting to common interconnected technologies and automated procedures in a coordinated, international approach to air traffic control services are key factors of improvement as regard infrastructure-related fuel use efficiency gains.

Several programmes have been launched, particularly ambitious and well-structured in Europe and the USA, to modernise air navigation systems. The SESAR programme (Single European Sky ATM Research) will merge the 36 current European flight control zones into 15 functional airspace blocks to improve air navigation services' performance in the highly complex, concentrated European airspace (70% flights concentrated into just 14% of the available airspace). It is expected to triple European airspace capacity by 2020, improve safety by a factor of ten, halve the costs of providing air navigation services and reduce the environmental impact per flight by 10% over 2005 levels. In the

USA, the NextGen programme (Next Generation Air Transportation System) is expected to reduce delays by 35-40% in 2018 compared with today's system. Table II-3 presents estimates for fuel savings and $CO_2$ emissions abatement that are expected from these two programmes.

**Table II-3 –Fuel savings and $CO_2$ emissions abatement with SESAR and NextGen**

| | SESAR | | | NextGen | | |
|---|---|---|---|---|---|---|
| | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 |
| **Fuel savings** (million tonnes per year) | 0.3 | 3.9 | 5.6 | 0 | 5.3 | 10.8 |
| **$CO_2$ emissions abatement** (million tonnes per year) | 0.8 | 12.2 | 17.7 | 0 | 16.7 | 33.9 |
| **Net cost savings** ($ billions) - Jet fuel @ $85/b | 0.5 | 7.6 | 10.3 | 0 | 7.1 | 15.1 |

*Source:* ATAG (2010).

Overall cost of the NextGen programme could range from $29 billion to $42 billion, with airlines bearing half the cost for the equipment of their fleets with the appropriate avionics equipment needed to realize the full benefits of NextGen technologies and procedures (GPS devices are valued more than $200,000 per plane) (GAO, 2008).

Besides, the design by air navigation service providers of new take-off, cruise and landing procedures and routings can also provide significant efficiency improvements. New departure routes alone, implemented at one airport provided reduction in departure delays of more than 2.5 minutes per flight, allowing for $35 million annual fuel savings annually from 2006 to 2008 (ATAG, 2010).

Similar modernisation is under way for procedures into airports. For instance, continuous descent operations (CDO) provided, in trials, up to 40% fuel savings during the approach phase, which translates into between 50 and 150 kg of fuel per flight. CDO furthermore allows for reduced fuel consumption (about 25-40% lower) during the last 45km of the flight (ATAG, 2010). As It has been estimated that wide adoption of CDO approaches procedures could provide fuel savings up to 150,000 tonnes per year in Europe alone (ATAG, 2010).

Overall, lessons learned from the ASPIRE (Asia and South Pacific Initiative to Reduce Emissions) experimentations aiming at the "perfect flight" tend to demonstrate that the optimisation of airport and air navigation infrastructure and procedures in every phase of flight preparation and operation can lead to a saving of over 4,500 litres of fuel per flight (13 tonnes of $CO_2$). Such achievements involve last-minute fuelling for better adjustment of fuel boarding to the actual passenger load, using the airport's fixed electrical power systems on the ground rather than the aircraft's APU, exploiting tail-winds during cruise, as well as operating a continuous descent approach procedure (ATAG, 2010).

Ultimately, it appears that collaborative decision-making (CDM), which consists of better coordination and sharing of timely data between airlines, airports and air traffic management to reduce delays and waiting times on the ground (queue-up while taxiing out, before take-off, or while taxiing in, before access to terminal gates) could be a source of substantial efficiency gains. In the USA, fuel burning costs from on-the-ground delays to airlines' schedules have been estimated over $5 billion in 2008 (ATAG, 2010).

The cost of $CO_2$ emissions abatement through the infrastructure pillar of fuel use efficiency can be assessed from programmes for which sufficient data are provided. For instance, based on financial information provided by GAO on all 31 sub-programmes included in NextGen over the 2005-2024 period (GAO, 2008), and assuming *i)* an even distribution of each sub-programme's overall investment costs over its completion period, *ii)* an even distribution of aircraft equipping costs over 20 years for a total amount of $14 billion, *iii)* a constant $85 jet fuel price per barrel (in 2008$), and *iv)* a 10% discount rate, the potential abatement from the NextGen programme over the period 2010-19 are estimated around 75.1 million tonnes of $CO_2$. Corresponding abatement costs (calculated by subtracting fuel savings from overall investment from 2005 to 2019 and aircraft equipping costs) average 2008$ 129 per tonne of $CO_2$.

In Europe, overall cost of the SESAR could be close to €32 billion, shared between three different phases: the definition phase (2005-2008) bore a cost of €60 million, the development phase (2008-2013) will bear an estimated cost of €2.1 billion, and finally the deployment phase (2013-2020) has an estimated cost of €30 billion over the period 2008-2025 (EC, 2011c). Based on this financial estimates and assuming *i)* an even distribution of each phase's costs over its completion period, *ii)* a constant $85 jet fuel price per barrel (in 2008$), *iii)* a 1.47 $2008/€2008 exchange rate, and *iv)* a 10% discount rate, the potential emissions abatement from the SESAR programme over the period 2010-19 are estimated around 64.7 million tonnes of $CO_2$. Corresponding abatement costs average 2008$ 111 per tonne of $CO_2$.

Full assessment of the abatement potential from the fuel use efficiency infrastructure levy at a global scale would require detailed information about other on-going or future optimisation programmes for air navigation and airport infrastructure and procedures worldwide. In the absence of such information, some general observations might still be useful, in a top-down approach, to grasp the complexity of further optimising global aviation infrastructure:

∴ While local optimisation of approach procedures into airports or air navigation routes design in a specific country meet both the airlines' need for increased cost efficiency and the country's quest for energy savings – which makes it a priority in emerging countries with fast-developing aviation markets and growing energy supply concerns such as China –, aviation infrastructure modernisation programmes involving international cooperation among countries often raise the questions of national security (for the choice of entry/exit points into the national airspace for instance) and sovereignty (for the defragmentation of airspace management for instance). Only in certain regions of the world willing to embrace cooperative decision-making beyond those critical restrictions will such international programmes reach full potential, as will hopefully be the case in Europe.

∴ Besides, both NextGen and SESAR programmes demonstrate that ambitious infrastructure modernisation programmes necessarily involve a strong technological content, thereby requiring significant investment and strong financial support from governments. Thus the replication of such programmes at a global scale, and particularly in emerging and developing economies, where aviation is booming, raises the itchy question of technology transfers' channels and financing.

∴ Finally, when dealing with such growth trends as can be observed in the aviation sector worldwide, the question of capacity saturation arises. Dealing with congested gateways has become increasingly crucial for the sector to keep up with demand's momentum. According to Airbus, 72% of worldwide traffic currently operates through 114 airports. If congestion might force infrastructure managers to accelerate systems and procedures modernisation (by increasing infrastructure charges if need be), the European experience tends to show that physical capacity limits can be pushed far beyond what was deemed feasible twenty years ago. The development and large-scale deployment of intelligent flow management systems could make room for further traffic densification with equivalent safety performance.

## 2.3 Abatement potential from fuels' carbon content

Some potential for abating emissions from the aviation sector may lie in the development of low-carbon content alternative jet fuels. Research in this area has gathered speed in the past few years thanks to the increase in kerosene prices and to the emergence of aviation emissions reduction projects. The challenge is nonetheless significant, since kerosene is almost the only fuel able to meet highly restrictive specifications (set up in the 1950s) for the safe use, transport and handling of fuels in aviation. Those specifications include: *i)* high energy density for compatibility with aircraft tank capacity and with long ranges, *ii)* thermal stability over a wide range of temperatures (from -50°C to +150°C approximately) for high altitude flights and injector deposit issues limitation, *iii)* viscosity, lubrication properties and limited corrosiveness for compatibility with metal and polymers, and *iv)* limited sulphur and aromatic content for emissions reduction.

In the short- and medium- terms, high investment costs in equipment and facilities lead to focus on so-called "drop-in" alternative jet fuels; i.e. alternative fuels that could be used for current aircraft without heavy modifications in equipment (aircraft or engine) or infrastructure, and be blended with current, conventional jet fuel. Indeed, the use of liquid hydrogen could enable the abatement of a major part of aviation emissions, but will presumably not be a credible option before 2050 since currently operated fleets would not be able to run on liquid hydrogen and the whole supply chain would have to be redefined. Main paths which have proved technically suitable in the short- to mid-term for the production of "drop-in" alternative jet fuels thus include synthetic liquid fuels from fossil resources (from natural gas or from coal to liquid fuel, named respectively GtL and CtL), synthetic liquid fuels from biomass or waste (BtL and WtL), as well as fuels from hydrogenated vegetable oils (HVO). Those options, however, have quite heterogeneous merits with regards to environmental sustainability on the one hand, and economic viability on the other hand:

- ∴ Synthetic fuels from fossil resources (CtL and GtL) have been experimented since the 1920s. Their use in aviation was first experimented by South Africa in 1999 for CtL (in a 50% blend with conventional jet fuel, then in 2008 with a pure-solution), and by Qatar in 2008 for GtL (in a 40% blend). Introduced on a large scale, they may constitute potential solutions to jet fuel supply and jet fuel prices volatility issues. Nonetheless, GtL (resp. CtL) are assessed to engender $CO_2$ emissions 1.15 (resp. 2 to 2.4) times higher than conventional jet fuels on a life-cycle assessment basis ($EQ^2$, 2010). It can be noted, however, that the environmental balance of these alternative fuels derived from fossil resources might be enhanced by the introduction of carbon capture and storage in the production of power that is needed for the fuel synthesis process (lifecycle emissions of synthetic jet fuels could then be reduced to 0.8 to 1.3 times those of conventional jet fuel) ($EQ^2$, 2010). Furthermore, these synthetic fuels tend to reduce emissions of particles at high altitudes and therefore limit the formation of contrails. Finally, the set up of industrial facilities for CtL and GtL lays the ground for large-scale production of BtL ad WtL fuels when those processes will have reached maturity.

- ∴ Synthetic fuels from biomass (mainly forestry and agriculture waste for BtL) and other renewable sources (such as urban waste for WtL) are based on the same process used for CtL and GtL, which theoretically allows for a wide range of inputs. Subject to the effective sustainability of biomass supply (*i.e.*, in particular, minimizing direct and indirect land use and land use change effects), they might allow for emission reduction higher than 90% as compared to conventional jet fuels, on a life-cycle assessment basis (E4Tech, 2009). Their production cost, however, is much higher than CtL's and GtL's due to some additional operations of "gas cleaning" included in the transformation process to deal with the heterogeneous composition of biomass and waste inputs as compared to coal and natural gas, for which technological readiness is not complete. The first large-scale facilities could start production in 2012-13 (resp. 2014) for BtL (resp. WtL).

∴ Lastly, fuels derived from Hydrogenated Vegetable Oils (HVO) are based on processes which are currently used for treating crude oil intermediate distillates. The HVO process already provides biodiesels for road transport. The aviation sector, however, is committed to avoid using biofuels derived from crops that compete with agriculture and food crops, whether directly (competition on land) or indirectly (competition on water or human resources) (e.g. sugar cane, palm oil, rapeseed, etc.). Therefore, the sector could avoid resorting to common energetic crops such as sugar cane, palm oil or rapeseed, and rather focus on new crops such as jatropha, camelina, halophytes or micro-algae. These various HVO crops present both heterogeneous maturity levels with high uncertainty on the timeframe for commercial availability, and uneven, variable potentials for emission reduction (with expectations up to 65% emissions abatement for jatropha HVO and 85% for camelina HVO, subject to the management of land use change issues) (E4Tech, 2009).

Recent studies have shown there is a significant trade-off between pathways and feedstock as far as large-scale development of aviation-compatible biofuels is concerned. Indeed, while the HVO pathway comes down to create a relatively cheap plant with 85% of final product cost determined by feedstock, the BtL process requires a much higher initial investment but would accommodate cheap feedstock (even urban waste).

Overall, while many trials since 2008 have been successful in proving the feasibility of an alternative fuel pathway for aviation, commercial availability of low-carbon alternative fuels might not be achieved by 2015, and maybe not even by 2020. The $EQ^2$ study assesses that the BtL process can only reach economic viability in a high conventional jet fuel price scenario (around $130/barrel). In such a scenario, the BtL path for alternative jet fuels could reach a breakeven point around 2018. A much higher price scenario for conventional jet fuel (around $160/barrel) would bring forward the breakeven point to 2013 (E4Tech, 2009). BtL competitiveness is subject to technology learning and economies of scale, as well as availability of relatively low-cost biomass. Production costs for the HVO path are not accurately known, especially when using unconventional crops such as jatropha, camelina, halophytes or algae. Over the last 5 years, the monthly prices of vegetable oils derived from conventional energy crops have shown a strong correlation to crude oil prices above a $60/barrel threshold (under this threshold, no correlation could be proven and vegetable oils prices are assumed constant). Based on the assumption this price correlation should prevail in the future, the HVO path for alternative jet fuels might not reach its breakeven point by 2050. On the contrary, based on the assumption that vegetable oils prices will follow their historical levels, the HVO path might then be cost-competitive in 2015 at the latest (in a low oil price scenario) or as soon as they are technically available. In any case, it is currently estimated that vegetable oils derived from unconventional energy crops will not be largely available on the market until they are produced at a cost close to the cost of conventional energy crops oils, i.e. $400 per tonne of vegetable oil. Commercial introduction could thus occur around 2012 for jatropha and camelina, and around 2018 for micro-algae (E4Tech, 2009). Table II-4 presents current estimates for the production costs of sustainable alternative jet fuels through the BtL and HVO paths.

**Table II-4 –Estimated production costs of BtL and HVO biofuels for aviation**

| | Production cost estimate in 2010 | $/barrel |
|---|---|---|
| **BtL**<br>CBtL process (co-production of BtL with CtL) | $0.52-0.63 /litre | 83 - 100 |

| | | |
|---|---|---|
| Pure BtL process | ≈ $1.6 /litre | ≈ 252 |
| **HVO** – *High uncertainty on production costs*<br>Camelina oil<br>Jatropha oil<br>Photosynthetic micro-algae oil | <br>$380/tonne<br>$350-500/tonne<br>$900/tonne | N.A. |

*Source:* E4Tech (2009).

Competition with the automotive market is a key issue when it comes to develop a sustainable biofuel pathway for aviation. Recent estimates tend to show that aviation's share of greener fuels will be similar to substantially less than the current cut of crude oil for aviation. Specific support policies would be necessary to expand the sustainable biofuels contribution for aviation. Low maturity of preferred biofuels pathways for aviation is already an additional challenge to the necessary scale up from experimental scale to industrialised scale of both processing and feedstock production. But due to its relative small share of the fuel market, aviation might face an even greater challenge than automotive to ensure effective access to the biofuels market.

Several scenarios for incorporation of low-carbon alternative jet fuels have been put forward by the industry. The IATA currently makes the assumption that a 6% mix of second generation sustainable biofuels could be available by 2020, thus leading to a 5% reduction in $CO_2$ emissions in the sector (IATA, 2009c). Based on IATA's most realistic scenario for biofuels' development in aviation, and assuming *i)* a progressive increase in biofuel incorporation from 0.1% in 2011, to 6.1% in 2020 (with an additional 0.5 percentage point yearly from 2011 to 2017, and one additional percentage point from 2018 to 2020), *ii)* investment costs of €500 million per plant (each plant based on Neste's plant in Singapore that produces 1 billion litres BtL biofuel) (E4Tech, 2009), *iii)* a constant $85 jet fuel price per barrel (in 2008$), and *iv)* a 10% discount rate, the potential emissions abatement from the introduction of alternative jet fuels over the period 2010-19 are estimated around 137.2 million tonnes of $CO_2$. Corresponding abatement costs (calculated by subtracting conventional fuel cost savings from biofuels' investment and production costs over the 2010-2019 period) average 2008$ 217 per tonne of $CO_2$.

These results call for several comments about the effective costs and benefits of reducing aviation's emissions through the development of sustainable biofuels pathways:

∴ Firstly, availability of biomass and sustainability of biofuels' production will require further analysis along the experimental and development phases of the different biofuels' pathways that have been identified as suitable for aviation. Indeed, currently available data do not provide a good enough understanding of all parameters and outcomes involved to accurately assess potential emissions abatement (and their costs) that can be achieved in aviation thanks to sustainable biofuels. The challenge for policy-makers is twofold: on the one hand, technological lock-ins may emerge from this information deficit if policy measures were to be taken too early, but on the other hand sufficient investment may never be found to launch an aviation-compatible, sustainable biofuels industry if policy measures do not bring long-term visibility to a capital-intensive industry in its infancy.

∴ Secondly, it must be emphasized that biofuels-derived emission abatements are not as environmentally virtuous (nor probably as economically profitable in the long run, in a world characterised by limited natural resources) as those obtained through fuel use efficiency gains. What is more, the large-scale deployment of biofuels could significantly reshape the merit order of other emissions reduction levies. It would indeed mechanically reduce the potential for emissions abatement through fuel use efficiency levies, as well as it would increase the corresponding abatement costs, since the lower carbon content of fuels would translate into lower emissions from each unit of fuel burned. This should be accounted for in the framework of a long-term assessment of aviation's GHG emissions abatement potential and costs.

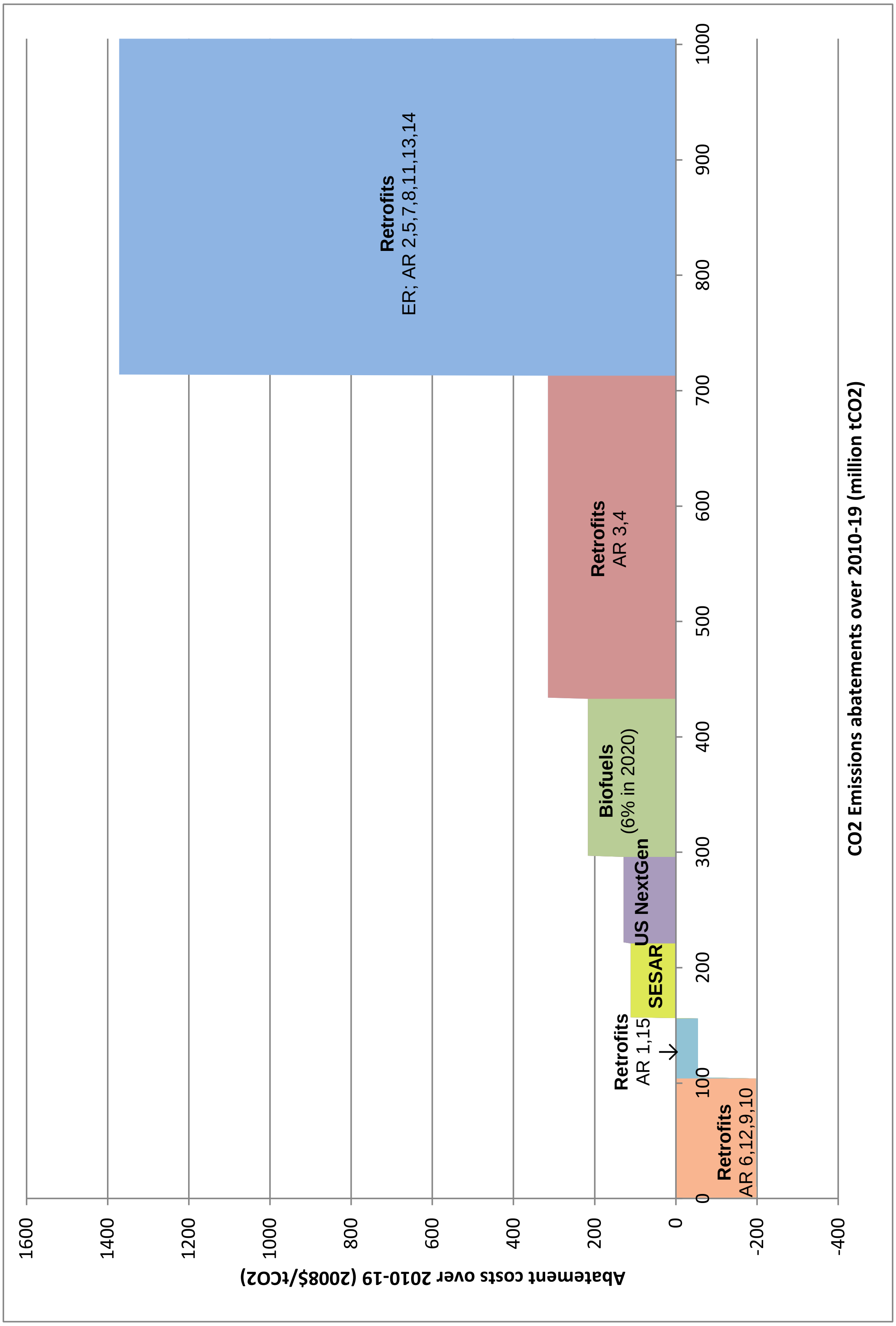
## 2.4 Drafting a mid-term merit-order curve for $CO_2$ emissions abatement in aviation

Based on the assessments produced in this study for potential emissions abatement in the period 2010-19 and their corresponding average costs on the same time scale, it is possible to draft a simplified mid-term merit-order curve. Merit-order curves are used in the power generation market to rank available sources of electric generation in ascending order of their short-run marginal costs of production, so that those power plants with the lowest marginal costs are first brought online to meet demand. Here, we suggest using a similar graphic illustration to rank available levies for emission reduction in aviation in ascending order of their mid-term (2019 horizon) costs of implementation.

Provided that it can be further refined using the most accurate data available in the industry for each levy's assessment and combining top-down and bottom-up approaches wherever possible, it seems that such a merit-order curve could make a useful decision-making tool for prioritizing policies and measures to be implemented in order to reach a defined emission reduction target in the aviation sector and anticipating the corresponding costs to the industry. Figure 9 illustrates the non-exhaustive merit-order curve for seven levies or groups of levies that were analysed in this paper: four groups of technology retrofits levies (see Table II-2 for detailed information), two infrastructure modernisation levies (the US and EU programmes, NextGen and SESAR), and the biofuels' levy.

These rough estimates show that just a bit more than 150 million tonnes of $CO_2$ could be abated worldwide from 2010 to 2019 using negative-cost levies (selected technology retrofits), which would represent less than 2% of total $CO_2$ emissions over the period. Infrastructure modernisation levies implemented in Europe and the US might bring a further abatement of nearly 140 million tonnes of $CO_2$ (for a total 3.6% reduction of total emissions over the period 2010-2019), at a cost ranging from \$110 to \$130 per tonne.

**Figure 9 – Draft mid-term merit-order curve for emission abatements in the aviation sector**



# 3. PRICING CARBON IN THE AVIATION SECTOR

The introduction of a price on carbon in the aviation sector is likely to modify the basic interactions among the different actors of the aviation system. Both environmental efficiency and economic efficiency are likely to be influenced by the choice of the right economic instrument to convey this new price signal to the actors. The European initiative to include aviation in the EU emission trading scheme from 2012 might teach some valuable lessons about carbon pricing in a sector that is characterised by diffuse emissions, capital-intensive activities and relatively high abatement costs compared to other sectors of the economy.

## 3.1 Impacts of a carbon price on the aviation ecosystem

The aviation sector is a complex ecosystem, with some very specific characteristics compared to other sectors of the economy.

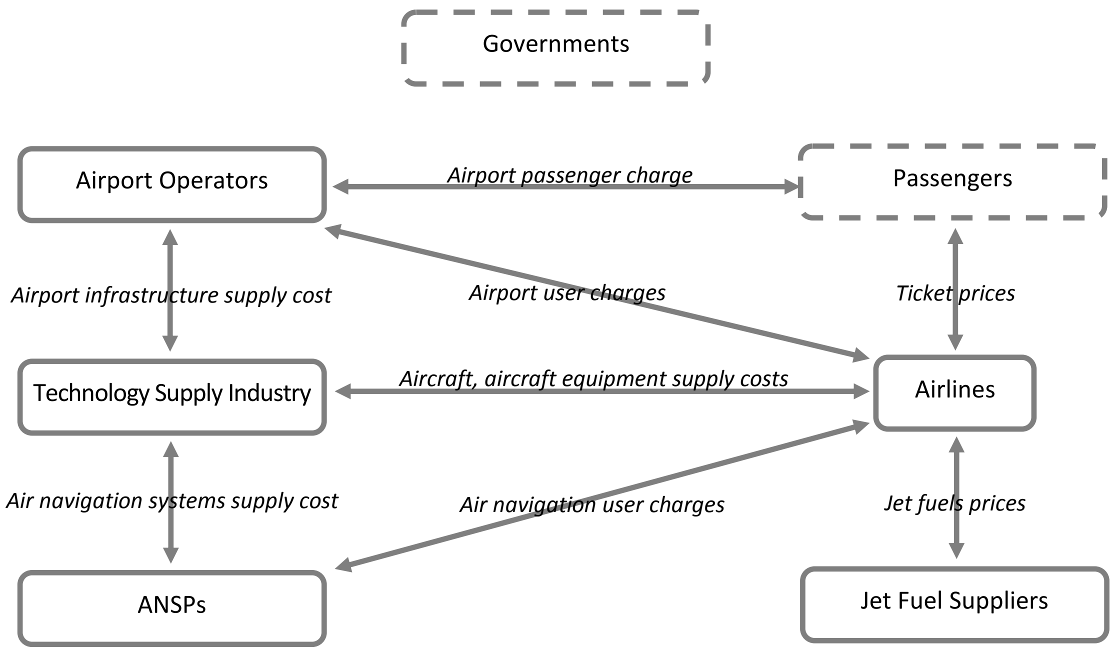
∴ First, not unlike other sectors, it has a history of strong state control. Aviation stakeholders, be they airlines, airport operators, aircraft manufacturers, oil companies or air navigation services providers (ANSPs), most commonly derive from national public entities. This has had a significant impact in the development of open competition practices.

∴ Besides, as already mentioned, aviation is both a technology-intensive and a capital-intensive sector, with a heterogeneous value chain. Considering the commercial aviation value chain, it must first be noted that commercial airlines usually have high revenues and equally high costs, so that they have recorded an average 2% operational profit over the last 25 years according to ICAO statistics. Conversely, major airport operators usually record operating margins around 20% (SESAR, 2006), and equalization schemes exist in many countries to help funding investments in non-profitable airport infrastructure on grounds of country planning considerations. ANSPs' pricing is usually based on cost recovery, so these actors normally do not make profits or losses. Operating margins in the technological supply industry (providing for aircraft, equipment, ATC systems, airport facilities, etc.) are usually in the 5-10% range, while they are rather in the 10-15% range for major oil companies in the field.

∴ Finally, the academic literature underlines the high interdependency of the global aviation industry, as opposed to the road transport sector for instance (Sgouridis, 2010). In particular, the aviation industry is reported to exhibit a tight coupling of the value chain (e.g. for the interconnection between operational strategies and financing) and to be prone to cyclical fluctuations in profitability that ultimately influence size and technological characteristics including fuel consumption efficiency.

Interactions among hereinabove mentioned actors of the aviation ecosystem are complex, for which main value drivers are basically information and price. Figure 10 suggests a simplified vision of the aviation ecosystem's main actors and their economic interactions.

**Figure 10 – Main actors of the aviation sector and their economic ties**




*Source:* the author, based on SESAR (2006) and Sgouridis (2010).

The introduction of a carbon price in this complex ecosystem is likely to impact many of the economic ties among actors. We hereinafter try and qualify these impacts, and roughly quantify some of them. Doing so, it is interesting to bear in mind that a $85 per barrel price level for conventional jet fuel already corresponds to an implicit carbon price of $212 per tonne of $CO_2$. Therefore, current levels of carbon prices ($22 per tonne of $CO_2$ on the EU ETS in 2010) would translate into a 10% increase in conventional jet fuel prices.

∴ *Jet fuels prices.* Carbon pricing is likely to have a direct effect on the relative prices of fuels, in accordance with their respective carbon content. As mentioned by several studies in the field ($EQ_2$, 2010; E4Tech, 2009), current levels of carbon prices (around $20 per tonne of $CO_2$) are not likely to tremendously impact the short-term share of biofuels in total aviation fuel supply since expected supply costs of sustainable alternative jet fuels from BtL and second generation feedstock HVO pathways are over twice or three times the current level of conventional jet fuel. However, carbon pricing could bring forward in time the breakeven point of sustainable alternative jet fuels with conventional jet fuels.

∴ *Ticket prices.* Carbon pricing is likely to have an indirect effect on traffic demand side. Specialised literature usually assesses carbon cost pass-through from airlines to passengers in a 50% to 100% range of magnitude (Standard & Poor's, 2011; Morrell, 2009; EC, 2006; and others). Currently observed price-elasticities of air transport demand under such cost pass-through assumptions generally lead these studies to conclude that current carbon prices levels will have a limited impact on air traffic growth. Potential carbon leakage related to the risk that traffic is diverted from airlines under a carbon pricing scheme to the benefit of other operators is usually also assessed to be limited under current price levels for carbon (EC, 2006, Standard & Poor's, 2011). However, potential negative impacts on demand through cumulated slowdown in traffic growth and traffic diversion are likely to translate into deteriorated profitability for airlines covered by a carbon pricing scheme, subject to the evolution of carbon price levels.

∴ *Infrastructure user charges and technology supply costs.* Due to increased expectations of airlines as regards the environmental performance of technology and infrastructure provided to them by the technology supply industry, the ANSPs and the airport operators, carbon pricing is likely to have an indirect impact on the associated supply costs.

The role of governments is not described in Fugure 10 because they interact with virtually all actors of the aviation ecosystem through taxation at every level (e.g. air ticket tax, corporate tax, fuel tax, value added tax on services and equipment, etc.), and potentially through carbon pricing. An interesting specificity of carbon pricing over other fiscal interference by the governments is that, as economic literature usually recommends, the revenue withdrawn from the aviation ecosystem through carbon pricing (see section 3.2 for further detail on use of revenues from carbon taxes and emissions trading schemes' auctions), can injected back into the ecosystem through government funding of environment-oriented R&D activities as well as infrastructure upgrading. This benefit, on top of the environmental benefit of carbon pricing, is usually referred to as the 'double dividend' in academic literature.

## 3.2 Options for introducing a carbon price in the aviation sector

There are two main instruments for introducing a carbon price into the economy in general, and into the aviation sector in particular: taxes and emissions trading (CEC, 2011).

### *a. Carbon taxes on fuels*

A carbon tax is a tax that sets a price for $CO_2$ emissions: its rate is expressed in euros per tonne of $CO_2$ emitted. A carbon tax adjusts the relative prices of assets (e.g. aircraft, infrastructure) or energy sources (jet fuels) according to their respective carbon intensity. When this fiscal instrument is used, the public authorities set the carbon price, and the effects on emissions will depend on the reactions of the sector's agents.

When applied to fuels, taxes can have an effect both on overall fuel demand and on the relative market shares of different fuels. Up until the 1990s, fuel taxation in the transport sector was not viewed as a way of orienting buyers towards vehicles using the lowest-carbon fuels. Since then, the emergence of environmental concerns has tended to reorient existing taxation in favour of a stronger incentive to cut emissions. A carbon tax applied to the transport industry can make the highest-carbon fuels more expensive, thus favouring fuels that emit less or no $CO_2$; it can also make it more economical to purchase vehicles (e.g aircraft) with low emissions and/or encourage the industry to produce lower-carbon, more energy efficient vehicles.

A carbon tax encourages emission reduction where they are the least expensive: if a manufacturer has to pay a tax of €20 per tonne of $CO_2$ emitted, it is in his interests to carry out all emission-reducing investments costing less than €20 per tonne of $CO_2$ avoided. In this way he saves the difference between the tax he would have had to pay without making any investment and the cost of the investment. A tax therefore means that the overall cost of abating emissions is reduced compared to the introduction of a standards-based policy.

Moreover, the reinvestment of the revenue from the carbon tax can make the fiscal measure more efficient. Supporting R&D or funding critical infrastructure could be a way to boost the sector's advances towards low-carbon technologies, and therefore generate what economists call a double dividend.

Historically, the ICAO has recommended that all its contracting States shall exempt international air transport from taxes on fuel. Fuel exemptions clauses have therefore been included in most bilateral air services agreements (BASAs) worldwide. Thus, any country willing to cancel any fuel tax exemption previously agreed upon would need to renegotiate all impacted bilateral agreements, which in practical terms would be very much time- and resource-consuming. Conversely, the ICAO has voiced open support to the inclusion of aviation in existing emissions trading systems (also called cap-and-trade systems) consistent with the United Nations process.

### *b. Cap-and-trade systems*

In a greenhouse gas emissions allowance trading system, or "carbon trading", the public authority sets a quantitative emissions reduction objective and the market then sets the price of the emission allowance. The global emissions cap ensures that the environmental objective is met. The authorities set the total volume of emissions authorized by distributing or selling a limited number of allowances (1 allowance = the right to emit 1 tonne of $CO_2$); in this case we refer to regulation by quantities (as opposed to regulation by prices via a tax). The allowances are shared between participants, who can trade these rights among themselves.

On the other hand, emissions trading attaches a price to the release of greenhouse gases and enables the environmental objective to be achieved at a lower cost. To comply with the environmental restriction applied to them, actors can choose between reducing their emissions and purchasing allowance units in the market. In this way, agents whose marginal costs for emissions reduction are lowest have an incentive to further reduce their emissions so as to sell their excess credits to agents with higher costs. As a result, emissions are cut first in those entities where it costs least to implement the reduction.

In a similar way to a carbon tax, emissions trading can generate a double dividend. If some or all of the allowances are auctioned, the appropriate reinvestment of the revenue (support to R&D or critical infrastructure financing) can help trigger further progress in the fight against climate change.

### *c. Choosing the right instrument*

Although often viewed as very different, theoretically taxes and trading schemes have more similarities than differences. Incentive taxes and negotiable allowances depend on an equivalent price mechanism, in theory, from the point of view of its economic effects: with perfectly informed agents, these two instruments enable emission reduction efforts to be made at the lowest cost for the community. If introduced correctly, they can help make substantial savings compared to public actions conducted on the basis of mandatory standards.

However, the two instruments achieve a balance in different ways: in the case of a tax, the initial uncertainty concerns the amount of emissions reduction, while in the case of a trading system the uncertainty applies to their price. Another difference lies in the implementation and transaction costs, which are higher in the case of an emissions trading scheme. Furthermore, trading may not be affordable for small agents whose business often has no connection with financial activities. Finally, existing emissions trading systems have so far been applied to fixed installations, on the grounds that emissions at consumer level (from mobile sources) are much harder to measure than at producer level (from stationary sources). However, the European carbon market is going to include air transport as of 2012 and will provide a better understanding of carbon pricing mechanisms in the aviation sector using the cap-trade instrument.

## 3.3 The EU ETS initiative

The European Union is the first group of countries to have put in place an emissions cap-and-trade system to help reach their objectives under the Kyoto Protocol. The EU Emissions Trading Scheme (ETS) came into effect in January 2005. It covers emissions from almost 12,000 specified industrial plants in seven major sectors: power and heat generation, refining, cement, glass, paper, iron and steel and coke ovens. Half of the EU's $CO_2$ emissions are covered, amounting to around 2 billion tonnes of $CO_2$ per year. In 2010, 5.2 billion allowances were traded in the European emissions marketplace, for an average price per unit of around €14 over the year (World Bank). A little more than a fifth of these transactions were spot deals, while the rest were exchanged through derivatives contracts (forward, futures and options).

In November 2008 the European Commission adopted a Directive (2008/101/EC amending the original EU ETS Directive 2003/87/EC) to include air transport in the European Union Emissions Trading Scheme as from 2012. This flagship policy, which came into force in February 2009, allocates quantified $CO_2$ emissions reduction objectives for all airlines, both European and non-European, operating in the EU. In practical terms, the aviation sector is expected to cut its emissions by 3% in 2012 from historical emissions levels in the 2004-06 period and by 5% for every year of the 2013-20 period. The system applied to aviation emissions is a semi-open one in that aircraft operators will be able to buy allowances on the existing carbon market, but stationary sources covered by the EU ETS will not be permitted to surrender aviation allowances (EUAAs) for their compliance.

The aviation part of the European Trading Scheme covers all flights departing from or arriving at airports located in any of the 27 EU Member States or the three associated non-EU States from the European Economic Area, namely Norway, Iceland and Liechtenstein. A number of exemptions have been introduced, however, mainly in order to reduce the scheme's overall administrative costs. A preliminary list of over 4,000 aircraft operators covered by the European scheme as of 2012 has been published by the Commission.

**Table III-1 – The main features of the EU ETS for aviation**

| | |
|---|---|
| **Scope** | $CO_2$ emissions from all aircraft departing from or arriving at an airport in any of the 27 EU Member States |
| **Exemptions** | ▪ Aircraft with a maximum weight below 5,700kg<br>▪ Military, rescue, emergency medical service or humanitarian flights<br>▪ Flights of heads of third-party states, or their ministers |
| ***De minimis* threshold** | ▪ Airlines operating flights with total emissions less than 10,000 tonnes<br>▪ Airlines operating fewer than 243 flights per 4-month period over 3 successive periods |
| **Historical emissions** | Mean of 2004-2006 emissions: 219 million tonnes $CO_2$ |
| **Emissions cap** | ▪ 97% of historical emissions, calculated as the average of emissions over the 2004-2006 period, for year 2012<br>▪ 95% of historical emissions for every year of the 2013-20 period |
| **Allocation free of charge (benchmarking)** | ▪ 85% of total allocation in 2012<br>▪ 82% of total allocation every year of the 2013-20 period |

| | |
|---|---|
| | ▪ *Pro rata* allocation based on an emission/activity benchmark (ref. 2010) |
| **Auctioning** | ▪ 15% of total allocation<br>▪ *Pro rata* distribution of allowances to be auctioned according to each Member State's share in the total emissions for the reference year |
| **Special reserve** | 3% of total allocation, starting 2013, dedicated to new entrants and airlines with an increase in traffic higher than 18% a year between 2010 and 2014 |
| **Linkage with other markets** | ▪ Use of Kyoto credits limited to 15% of total allowances to be surrendered for compliance in 2012, then at least 1.5% during the 2013-20 period<br>▪ Semi-open scheme: stationary installations covered by the EU ETS are not allowed to use aviation allowances (EUAAs) for their compliance |
| **"Opt out" conditions** | When a non-EU country adopts measures to reduce its Europe-related emissions, the Commission may decide to exempt its flights from the scheme (Art. 25a) |

*Source:* CEC (2011).

Calculation of the total emissions cap for aviation will use the grandfathering method, based on the sector's historical $CO_2$ emissions, determined by the mean annual emissions in the calendar years 2004, 2005 and 2006. In 2012, the first year aviation is included in the ETS, the sector's total allocation will be capped at 97% of the historical emissions level. During the 2013-20 period, this cap will be lowered to a constant level of 95% of historical emissions.

From 2012 onward, airlines will have to purchase 15% of their EUAAs by auction. From 2013 onward, 3% of the total allowances will be placed in a special reserve for newcomers in the EU civil aviation market and airlines whose business is rapidly growing. Thus aircraft operators will receive 85% of their allowances free of charge in 2012 and 82% over the period 2013-20.

For allowances that are meant to be allocated free of charge, although an allocation system based on grandfathering would be simple to implement, it could also have the major drawback of giving historically higher-polluting airlines larger shares of the total allowances. To avoid this situation, the allocation of allowances will instead use performance criteria within the framework of a benchmarking method.

The performance benchmark, expressed in allowances per tonne-kilometre, is obtained by dividing the total amount of allowances to be distributed free of charge by the total tonne-kilometres reported by the airlines. The amount of allowances allocated to each airline is then calculated by multiplying the tonne-kilometres data provided in the airline's application by the previously assessed benchmark.

This mechanism guarantees that all airlines are treated equally, since two operators with equal business activity over the monitored year will get the same amount of free allowances. As a result, airlines emitting less $CO_2$ in operating their fleets will be favoured, while the others will have an incentive to make further efforts to abate their emissions.

To meet their emissions cap under the EU ETS, airlines may either reduce their emissions or use their allowances (EUAA). In addition, they can purchase allowances of stationary sources (EUA) and Kyoto credits (CER, ERU). The sector as a whole is expected to be short of allowances throughout the period. Consequently, for compliance, airlines will have either to reduce their emissions or to buy allowances outside the aviation market.

Under a baseline scenario the net deficit of the aviation sector in 2012 is expected to be 51 million tonnes (CEC, 2011). If Kyoto credits are available in sufficient amounts, airlines will be able to import 39.5 million (i.e. 15% of the 263.5 million tonnes of verified emissions) and consequently they will be net buyers of 11.5 million EUAs in the carbon market. If now we assume that half of the deficit will be covered by emissions reduction achieved by the aviation sector, then Kyoto credits should be sufficient to cover the net deficit of 25 million tonnes in 2012. There will consequently be no demand for EUAs.

The demand for European allowances from the aviation sector is expected to increase during the 2013-20 period, mainly because of the overall reduced cap and the shift from 15% to 1.5% in the maximum permitted use of Kyoto credits. Hence, from 2013, aviation's net demand for EUAs is forecast to be 57 million tonnes without additional abatement and 27 million tonnes if airlines reduce emissions by 50% of their net deficit. By 2020, the aviation sector's need for EUAs will probably range between 50 and 100 million tonnes, depending on whether or not airlines manage to further reduce their emissions. Though these figures give a broad indication of aviation's net demand, they are only approximate since we do not know the future level of emissions abatement or the final limit on the import of Kyoto credits.

The inclusion of aviation in the EU ETS is thus likely to support the allowance price in the carbon market and could encourage further emission reduction from industries covered by the European scheme. It will also give impetus to research in aeronautics, especially the development of alternative fuels to replace conventional jet fuel.

# CONCLUSION

This study has shown that technology and airline operation levies for increasing fuel use efficiency, which have been key drivers of past emissions abatement in the aviation sector, may still hold significant potential for further abatement at a global scale in the coming decade. Some technology retrofits alone could provide up to 2% emissions reduction compared to the baseline scenario, at a negative cost to the sector.

On top of that, fuel use efficiency gains from infrastructure modernisation, which is among the sector's priorities for the coming decade, should provide a further 1.6% abatement compared to the baseline scenario. Full exploitation of that emissions abatement levy is however subject to substantial funding from the governments since associated abatement costs (around \$110-\$130 per tonne of $CO_2$) are not economically viable as such.

Besides, the development of sustainable alternative fuels pathways for aviation could generate further emissions abatement, though to a lesser extent than previously mentioned levies in the coming decade and provided that governments demonstrate strong support to R&D in this emerging capital-intensive industry.

The introduction of a carbon price in the aviation sector, whether it occurs through a tax or through a cap-and-trade system, is likely to modify anticipated equilibriums as regards potential for and costs of emissions abatement through the interference in the complex net of economic ties among the various stakeholders in the aviation ecosystem. On top of basic impacts identified in this paper, namely on relative jet fuels prices, on air ticket fares, and on infrastructure and technological supplies prices, it could be useful to further investigate the link between carbon pricing and future oil supply. Indeed, recent works have shown that climate policies tend to reduce the risk of loss due to future oil scarcity, as well as the uncertainty on future global wealth (Rosenberg, 2010). Now, aviation's exposure to the oil supply security challenge is particularly high due to the rather limited cut of conventional jet fuel in crude oil supply and to the competition on fuel it faces from other modes of transport.

Finally, the first years of the EU ETS' extension to the aviation sector should provide interesting insights as to the effective fostering of emissions abatement in this sector in connection with the introduction of a consistent price signal for carbon. In this respect, it might emerge from the European experience that carbon pricing is most relevant when designed as a part of a broader approach. Relevant public policies are likely to be required to send complementary, consistent signals to all stakeholders in the sector, with careful consideration being given to issues of comprehensibility and flexibility in order to avoid incentivising non-optimal investment and triggering technological lock-ins, as regards the development of sustainable biofuels for aviation for instance.

# LIST OF ACRONYMS

| | |
|---|---|
| ACARE | Advisory Council for Aeronautics research in Europe |
| AEA | Association of European Airlines |
| ATA | US Air Transport Association |
| ATAG | Air Transport Action Group |
| ATC | Air Traffic Control |
| ATM | Air Traffic Management |
| BtL | Biomass to Liquids |
| CDM | Collaborative Decision-Making |
| CDO | Continuous Descent Operations |
| CEC | Climate Economics Chair |
| CtL | Coal to Liquids |
| $CO_2$ | Carbon dioxyde |
| EC | European Commission |
| EIA | US Energy Information Agency |
| ERFP | European Research Framework Programme |
| ETS | Emission Trading Scheme |
| EU | European Union |
| EuroPIA | European Petroleum Industry Association |
| GAO | US Government Accountability Office |
| GDP | Gross Domestic Product |
| GHG | Green house gas |
| GtL | Gas to Liquids |
| HVO | Hydrogenated Vegetable Oil |
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organisation |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| ITF | International Transport Forum |
| NextGen | Next Generation Air Transportation System |
| OECD | Organisation for Economic Co-operation and Development |
| PARTNER | Partnership for AiR Transportation Noise and Emissions Reduction |
| RPK | Revenue Passenger-Kilometres |
| SESAR | Single European Sky ATM Research |
| UN | United Nations |

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# APPENDIX 1

## Overall assessment of greenhouse gas emissions from aviation

As suggested by recent studies, aviation's overall warming impact could be much higher than primarily assessed from $CO_2$ emissions alone. Indeed, besides $CO_2$, aviation emits other GHGs, such as nitrous oxides (NOx), methane ($CH_4$) and water vapour ($H_2O$). Those emissions have differentiated effects at different altitudes; in particular, at certain altitudes (around 10km), they contribute to the formation of cirrus clouds and contrails (IPCC, 1999). Currently, there is relatively high uncertainty about the net effects of all GHG emissions from aviation on global warming.

$CO_2$ is just one of several aircraft emissions that have radiative forcing effects. Others include nitrogen oxides, methane, water vapour and cloud formation. Table AI.1 summarizes main impacts and radiative forcing effects of aviation-related greenhouse gases. IPCC assessments reveal that overall radiative forcing of aviation-related GHG emissions, which was evaluated around 2.7 times the radiative forcing of $CO_2$ emissions alone in 1992 (IPCC, 1999), could in fact be closer to 1.9 times the radiative forcing of aviation-emitted $CO_2$ according to more recent studies (IPCC, 2007).

**Table AI.1 – The main atmospheric impacts and radiative forcing effects of aviation-related GHGs**

| Greenhouse gas | Impact on atmosphere chemistry | Radiative Forcing |
|---|---|---|
| **$CO_2$** | Direct warming effect<br>Not sensitive to altitude<br>Global impact | 18 mW/m$^2$ in 1992<br>25 mW/m$^2$ in 2000 (1.7% of total $CO_2$ RF) |
| **$O_3$ and $CH_4$ from NOx** | NOx induce chemical reactions that indirectly modify the atmosphere<br>Negative impact on $CH_4$ concentration (long lifetime, global impact); positive impact on ozone (short lifetime, local impact concentrated in the northern hemisphere) in troposphere and stratosphere | Globally neutral<br>(negative for methane, positive for ozone) |
| **$H_2O$** | Limited impact when emitted in troposphere (rapid hydrologic cycle); increased greenhouse effect when emitted in stratosphere (longer lifetime of $H_2O$ molecule)<br>Triggers the development of contrails | 2.5 mW/m$^2$ in 2000 |
| **$SO_2$ and soot** | Influence the formation and properties of clouds | Globally neutral<br>(negative for sulphates, positive for soot) |
| **Contrails** | Limited impact (small surface)<br>Only form around 10km altitude<br>May develop into cirrus clouds | 20mW/m$^2$ in 1992 with high uncertainty (between 10 and 60/70 mW/m$^2$)<br>10mW/m$^2$ in 2000 |
| **Total (without aviation induced cloudiness)** | | 48.5mW/m$^2$ in 1992<br>48.3mW/m$^2$ in 2000 |
| **Cirrus (Aviation induced cloudiness)** | Increased nebulosity<br>Limited cumulated impact as compared to $CO_2$ due to shorter lifetime<br>However, potential impact on climate due to large surface | High uncertainty<br>From 0 to 40mW/m$^2$ in 1992<br>From 10 to 80 mW/m$^2$ in 2000 |

*Sources:* Lee et al. (2009) from IPCC (1999, 2005).

However, using global warming power assessments as a metrics for the temperature variation induced by aviation-related GHG emissions during their lifespan in the atmosphere over a 100-year reference period, multiplying factors for overall aviation-related GHG emissions could be closer to between 1.1 and 1.4 times the global warming power of aviation $CO_2$ emissions alone. Indeed, global warming power depends on both the efficiency of the molecule as a greenhouse gas and its atmospheric lifetime. From this perspective, $CO_2$, which is the main GHG emitted by aviation, has a much lower global warming power than $CH_4$ (25 times higher than $CO_2$) and other major GHGs (300 to 23,000 times higher than $CO_2$).

Overall impact assessment of GHG emissions from a specific flight is all the more complex as flight conditions are of significant influence.

- ∴ Altitude is a key factor. Indeed, while $H_2O$ emissions have low impact in the troposphere, they have high impact in the stratosphere. Besides, NOx induce a variable quantity of $O_3$, with variable associated greenhouse effect, depending on altitude. Finally, the formation of contrails specifically occur around 10km altitude.

- ∴ Latitude is another important parameter. $O_3$ formed from NOx has a different impact depending on latitude.

- ∴ Temperature and humidity have significant impacts on contrails formation.

- ∴ Finally, flight time is of great importance for, by day, sunrays retrodiffusion by contrails and induced greenhouse effect by ice crystals can have balanced impacts, whereas, by night, the absence of retrodiffusion effect leads to a higher warming impact.

This sensitivity to flight conditions of aviation's impacts on the atmosphere reveals it might be interesting to adapt flight altitude in order to limit the formation of contrails (at higher altitude) under the condition that this adaptation is not made at the expense of $CO_2$ emissions, which have a longer lifetime in the atmosphere.

On top of these variations induced by flight conditions, it can be noted that the impact of increased engine efficiency on the overall greenhouse effect assessment of aviation might not be all positive. Indeed, while reducing $CO_2$ emissions, increased engine efficiency also translates into higher contrails formation. While contrails may have a rather low radiative forcing compared to that of $CO_2$ (uncertainty with regards to contrails' radiative forcing is still quite high though), they may under certain conditions develop into cirrus clouds whose impact – although also highly uncertain – might be up to 3 times that of $CO_2$ in terms of radiative forcing.

Thus, in order to assess the full effects of aviation taking into account all GHGs and their complex impacts on atmospheric chemistry, better scientific understanding and appropriate metrics are needed.

The IPCC, whose 1999 estimation of aviation's share in anthropogenic GHG emissions was 3.5% for 1992 (including both $CO_2$ and non-$CO_2$ induced effects), produced scenarios estimating that aviation's contribution could grow to 5% of the total anthropogenic climate change by 2050 in the absence of targeted mitigation action in the aviation sector. In its Fourth Assessment Report (AR4) published in 2007, IPCC revised its original estimation for aviation's share in anthropogenic climate change to 3.0% of total radiative forcing by all human activities for year 2005, with $CO_2$ aviation emissions amounting to 2% of global $CO_2$ emissions (IPCC, 2007). Further scientific information should allow for an even better understanding of all aviation-induced effects on climate by the time IPCC publishes its Fifth Assessment Report (AR5), which is scheduled to be completed in 2014.

## APPENDIX 2

### Methodology for airlines' operational expenses' breakdown

ICAO publishes data for operational revenues and expenses of scheduled airlines from its contracting member States.

Operating expenses as published by ICAO consist of 8 main categories. A more detailed breakdown is available for years 1990 to 2007, as follows:

- Flight operations expenses include *i)* flight crew salaries and expenses, *ii)* aircraft fuel and oil, *iii)* flight equipment insurance and uninsured losses, *iv)* rental of flight equipment, *v)* flight crew training (when not amortized), *vi)* other flight expenses.
- Maintenance and overhaul expenses.
- Depreciation and amortization expenses include *i)* normal depreciation of flight equipment, *ii)* normal depreciation of ground property and equipment, *iii)* extra depreciation (in excess of cost), *iv)* amortization of development and pre-operating costs, *v)* flight crew training (when amortized).
- User charges and station expenses include *i)* landing and associated airport charges, *ii)* route facility charges, *iii)* station expenses.
- Passenger services.
- Ticketing, sales and promotion.
- General administrative.
- Other operating expenses.

For the present study, we suggest to adopt a different breakdown of airlines' operating expenses in order to get a clearer view of airlines' focuses of interest. Four of the main cost categories remain unchanged from ICAO's original breakdown, namely: maintenance and overhaul expenses, user charges and station expenses, passenger services, and finally ticketing, sales and promotion.

However, it appeared interesting to suggest a different breakdown for flight operations expenses, depreciation and amortization expenses as well as other expenses, administrative or else:

- First, aircraft fuel and oil is isolated from other flight operations expenses to reveal potential evolution of airlines strategic behaviours as regards fuel prices.
- Then, flight equipment rental costs and flight equipment normal depreciation costs were summed to get a clearer view of flight equipment (e.g. aircraft) total costs to the airlines, be it owned or leased by the operator.

- ∴ Then, flight crew salaries and expenses and flight crew training (whether amortized or not) expenses were summed to get a clearer view of flight crew total costs to the airlines.

- ∴ Finally, all other costs were summed in a miscellaneous cost category including: *i)* general and administrative expenses, *ii)*, insurance, *iii)* normal depreciation of ground property and equipment, *iv)* extra depreciation, *v)* amortization of development and pre-operating costs, *vi)* other flight expenses, and *vii)* other operating expenses.

Table AII.1 retraces the evolution of the relative shares in total operating expenses of these 8 main cost categories over the 1990-2007 period. According to the suggested breakdown in operating costs, aircraft fuel occupied the number two position in airlines' main operating cost categories for the first in 2000. It then became airlines' first cost category in 2004 and has remained in this position so far. According to IATA, fuel amounted to 33% of airlines' total operating costs in 2008, before lowering to 26% in 2009 and 2010.

**Table AII.1 – Evolution of 8 main cost categories' relative shares in airlines' total operating costs, 1990-2007**

| Cost category | Share in total operating expenses | | | | |
|---|---|---|---|---|---|
| | 1990 | 1995 | 2000 | 2005 | 2007 |
| **User charges and station expenses** | 16.1% | 18.2% | 17.2% | 16.2% | 16.2% |
| **Maintenance and overhaul** | 11.4% | 10.6% | 10.6% | 10.2% | 10.3% |
| **Passenger services** | 10.3% | 11.1% | 10.0% | 9.3% | 8.7% |
| **Flight equipment** | 9.8% | 11.1% | 12.3% | 11.8% | 11.1% |
| **Flight crew** | 7.3% | 8.1% | 8.5% | 7.9% | 7.5% |
| **Ticketing, sales and promotion** | 16.3% | 15.6% | 12.7% | 9.1% | 8.5% |
| **Aircraft fuel and oil** | 15.1% | 11.4% | 14.4% | **22.2%** | **25.4%** |
| **Misc.** | 13.6% | 13.8% | 14.2% | 13.3% | 12.3% |

*Source:* the author, from ICAO.

Table AII.2 retraces the evolution of unit costs in the 8 suggested main cost categories, taking 1990 as reference year. Unit costs are obtained by dividing operating costs by traffic volume (scheduled revenue passenger-kilometres as reported by airlines from ICAO contracting States). These results reveal that airlines managed to keep unit operating expenses in all cost categories in a -20%/+20% variation range around their 1990 value, with the noticeable exception of fuel, which overshoot the 1990 value in 2004, before reaching 71% excess cost per RPK performed in 2007 compared to 1990.

**Table AII.2 – Evolution of 8 main cost categories' unit costs, 1990-2007**

| Cost category | Evolution in unit costs (1990 = 100) | | | | |
|---|---|---|---|---|---|
| | 1990 | 1995 | 2000 | 2005 | 2007 |
| **User charges and station expenses** | 100 | 112.1 | 98.4 | 97.3 | 101.6 |
| **Maintenance and overhaul** | 100 | 92.4 | 86.0 | 86.8 | 91.6 |
| **Passenger services** | 100 | 106.9 | 89.6 | 87.5 | 85.5 |
| **Flight equipment** | 100 | 113.0 | 115.5 | 116.6 | 114.6 |
| **Flight crew** | 100 | 110.7 | 108.0 | 105.0 | 104.0 |
| **Ticketing, sales and promotion** | 100 | 95.1 | 71.9 | 54.0 | 52.7 |
| **Aircraft fuel and oil** | 100 | 75.4 | 88.5 | 142.8 | **170.7** |
| **Misc.** | 100 | 101.1 | 96.2 | 94.7 | 91.5 |

*Source:* the author, from ICAO.

# APPENDIX 3

## Jet fuel type kerosene price evolutions

Historical jet fuel prices are available from different sources on different timescales. For this study, we chose to work on annual average data series published by Platt's in specialized media such as *Aviation Economist* or *Airline Business.* Available data for years 1982 to 2000 are median values for North Western Europe, Mediterranean and US cargo spot prices (monthly average values averaged over a year), while available data for years 2000 to 2010 are median values for Europe/Singapore cargo and US pipeline spot prices (monthly average values averaged over a year), with a 0.6% difference for 2000 values between the two methods. Table AIII-1 summarizes values that were used in this study.

**Table AIII.1 – Jet fuel spot prices, annual world average**

| Kerosene-type jet fuel spot price per barrel ($US, current) | | | | | |
|---|---|---|---|---|---|
| **1981** | - | **1991** | 26.7 | **2001** | 29.7 |
| **1982** | 39.9 | **1992** | 24.4 | **2002** | 28.5 |
| **1983** | 35.0 | **1993** | 22.0 | **2003** | 34.1 |
| **1984** | 33.5 | **1994** | 20.7 | **2004** | 48.8 |
| **1985** | 33.1 | **1995** | 20.5 | **2005** | 70.4 |
| **1986** | 19.3 | **1996** | 26.3 | **2006** | 81.8 |
| **1987** | 21.1 | **1997** | 23.3 | **2007** | 89.7 |
| **1988** | 19.9 | **1998** | 15.9 | **2008** | 124.0 |
| **1989** | 23.3 | **1999** | 21.1 | **2009** | 70.3 |
| **1990** | 30.5 | **2000** | 36.2 | **2010** | 91.1 |

*Source: Aviation Economist* and *Airline Business*, from Platt's.

Because kerosene-type jet fuel represents a limited cut of crude oil and is dedicated to a very specific, captive market, its spot prices usually register a 15 to 45% crack spread over crude oil spot prices. In times of crises, jet fuel prices generally rise higher and faster than those of crude oil and many other refined products. Table AIII.2 illustrates the evolution of jet fuel crack spread against crude oil over 20 years in Europe.

**Table AIII.2 – Jet fuel crack spread against crude oil in Europe, annual average**

| Amsterdam kerosene-type jet fuel spot price yearly average against Europe Brent spot price yearly average | | | |
|---|---|---|---|
| **1990** | +33% | **2000** | +30% |
| **1991** | +40% | **2001** | +26% |
| **1992** | +29% | **2002** | +17% |
| **1993** | +45% | **2003** | +24% |
| **1994** | +39% | **2004** | +32% |
| **1995** | +27% | **2005** | +31% |
| **1996** | +31% | **2006** | +25% |
| **1997** | +28% | **2007** | +24% |
| **1998** | +34% | **2008** | +31% |
| **1999** | +23% | **2009** | +15% |

*Source: EIA.*

Besides, kerosene-type jet fuel spot prices reveal much higher volatility than what is observed for crude oil. Table AIII.3 illustrates differences in standard deviation of daily spot prices for Amsterdam kerosene-type jet fuel on the one hand, for Europe Brent crude oil on the other hand. It appears while standard deviations in prices have been consistently higher for jet fuel than for crude oil in absolute terms over the period 1990-2009 in Europe, they have been very much similar however in relative terms.

**Table AIII.3 – Volatility of jet fuel and crude oil prices in Europe**

| | Standard deviation in daily spot prices, year average | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Amsterdam Jet fuel | | Europe Brent | | | Amsterdam Jet fuel | | Europe Brent | |
| | $/bbl | % of spot price | $/bbl | % of spot price | | $/bbl | % of spot price | $/bbl | % of spot price |
| **1990** | 12.0 | *38%* | 7.7 | *33%* | **2000** | 4.7 | *13%* | 3.4 | *12%* |
| **1991** | 5.1 | *18%* | 1.9 | *10%* | **2001** | 3.6 | *12%* | 3.4 | *14%* |
| **1992** | 1.5 | *6%* | 1.1 | *6%* | **2002** | 3.6 | *12%* | 3.0 | *12%* |
| **1993** | 1.1 | *5%* | 1.5 | *9%* | **2003** | 4.3 | *12%* | 2.5 | *9%* |
| **1994** | 0.8 | *4%* | 1.4 | *9%* | **2004** | 8.8 | *17%* | 5.6 | *15%* |
| **1995** | 1.1 | *5%* | 0.9 | *5%* | **2005** | 8.5 | *12%* | 6.2 | *11%* |
| **1996** | 3.7 | *14%* | 2.3 | *11%* | **2006** | 6.9 | *8%* | 5.9 | *9%* |
| **1997** | 2.3 | *9%* | 1.8 | *9%* | **2007** | 13.4 | *15%* | 11.8 | *16%* |
| **1998** | 1.9 | *11%* | 1.6 | *12%* | **2008** | 33.9 | *27%* | 28.9 | *30%* |
| **1999** | 5.8 | *26%* | 5.0 | *28%* | **2009** | 11.4 | *16%* | 12.3 | *20%* |
| **1990-2009** | **30.3** | ***70%*** | **24.2** | ***71%*** | | | | | |

*Source: EIA.*

Rather than having a structurally higher volatility compared to crude oil prices, jet fuel prices seem to be specifically sensitive to externally-induced price hikes for these hikes tend to cause the structural crack spread against crude oil prices to widen (see 1990-1991, 2000, 2004, and 2008). In the absence of proper jet fuel futures contracts, widening crack spreads can be source of greater uncertainty for airlines than the mere volatility of their fuel supplies' spot prices since companies can only partially hedge against those increases in jet fuel spot prices.